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Low NOx Strategy for Combusting High Nitrogen Content Fuels

Acurex Corp., Research Triangle Park, NC

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A LOW NO_X STRATEGY FOR COMBUSTING HIGH NITROGEN CONTENT FUELS

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16. ABSTRACT The report gives results of an evaluation of a multistaged combustion burner (designed for in-furnace NOx control and high combustion efficiency) for high nitrogen content fuel and waste incineration application in a 1.0 MW package boiler simulator. A low NOx precombustion chamber burner has been reduced in size by about a factor of two (from 600 to 250 ms first-stage residence time) and coupled with: (1) air staging, resulting in a three-stage configuration; and (2) natural gas fuel staging, yielding up to four stoichiometric zones. Natural gas, doped with ammonia to yield a 5.8% fuel nitrogen content, and distillate fuel oil, doped with pyridine to yield a 2.0% fuel nitrogen content, were used to simulate high nitrogen content fuel/waste mixtures. Minimum nitric oxide (NO) emission levels of 160 and 110 ppm (corrected to 0% oxygen, C2) were achieved for the natural gas and fuel oil tests, respectively, corresponding to about 85% reduction in NOx emissions compared to uncontrolled emissions from a conventional burner mounted on a 0.7 MW commercial package boiler. Under the conditions tested, net chemical destruction of NO via reburning does not seem to be evident. This may be due to the existence of rather low primary NO concentrations before the application of reburning. However, a beneficial dilution caused by reburning may provide lower NO emissions.

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ABSTRACT

A multistaged combustion burner designed for in-furnace NO_x control and high combustion efficiency has been evaluated for high nitrogen content fuel and waste incineration application in a 1.0 MW package boiler simulator. A low NO_x precombustion chamber burner has been reduced in size by approximately a factor of two (from 600-250 ms first-stage residence time) and coupled with 1) air staging, resulting in a three-stage configuration, and 2) natural gas fuel staging, yielding up to four stoichiometric zones. Natural gas, doped with ammonia to yield a 5.8 percent fuel nitrogen content, and distillate fuel oil, doped with pyridine to yield a 2 percent fuel nitrogen content, were used to simulate high nitrogen content fuel/waste mixtures. Minimum nitric oxide (NO) emission levels of 160 ppm and 110 ppm (corrected to 0 percent oxygen, O_2) were achieved for the natural gas and fuel oil tests, respectively. These results correspond to approximately 85 percent reduction in NO_x emissions compared to uncontrolled emissions from a conventional burner mounted on a 0.7 MW commercial package boiler. Under the conditions tested, net chemical destruction of NO via reburning does not seem to be evident. This may be due to the existence of rather low primary NO concentrations before the application of reburning. However, a beneficial dilution caused by reburning, as applied here, may provide lower NO emissions (on a ppm or lb/10^6 Btu basis) along with no loss in heat output.

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SECTION 1

INTRODUCTION

The family of nitrogen oxide compounds, including nitric oxide (NO) and nitrogen dioxide (NO_2), is generally referred to as "NO_X." These NO_X species are formed during the combustion of coal, oil, and natural gas by the reduction and oxidation of molecular nitrogen (N_2) and nitrogen contained in the fuel. NO_2 is a poisonous gas that the United States Environmental Protection Agency (EPA) has designated as a criteria pollutant because of its harmful effects to human health.[1] In addition, NO_X emissions are known to contribute to the formation of photochemical oxidants and are precursors, along with sulfur oxides (SO_X), of acid precipitation. Two more areas of concern are emerging regarding NO_X levels in the atmosphere. First, forest damage as a result of acid precipitation, reported to be extensive in the Federal Republic of Germany,[2] has been linked with increasing NO_X levels. Second, increasing levels of atmospheric nitrous oxide (N_2O) have been measured, levels that are predicted to contribute to both a decline in the abundance of stratospheric ozone and an increase in climatic warming.[3] Studies of N_2O and NO concentration in experimental flames and in flue gases indicate that a correlation may exist between these two gases formed in combustion processes.

The EPA estimates that about 20 million tons (18,000 Gg) of NO_X are emitted annually from stationary and mobile sources in the United States. Unlike SO_X emissions, NO_X emissions are increasing.[4] Coal- and oil-fired utility and industrial boilers account for over half of these NO_X emissions. Only 15 percent of the stationary NO_X sources are regulated by EPA's New Source Performance Standards (NSPS); the remainder must be addressed with retrofit technologies if significant NO_X emission reduction is to be realized. Another NO_X control problem is posed by the potential of incinerating high nitrogen content wastes in industrial boilers. While incineration of these materials would not constitute a significant increase in the overall national NO_X emission level, individual plant emissions may be sufficient to cause a local NO_X problem that would prevent governmental permitting of on-site incineration. As

thermal destruction is an attractive alternative to landfill storage of wastes, the need continues for developing high efficiency, low NO_x combustion technologies.

Most NO_x in stack combustion gas is NO. Much is known about the mechanisms of NO formation in flames, both from molecular nitrogen (source of thermal NO) and from fuel-bound nitrogen (source of fuel NO). Thermal NO can be reduced by decreasing peak flame temperatures. Fuel NO is very sensitive to reactant stoichiometry and fuel-rich conditions promote N_2 formation over NO formation. Laboratory studies and field test data have established the importance of fuel NO to the total emission of NO_x from residual fuel oil and coal flames. Therefore, minimizing NO_x formation in flames typically involves controlling air and fuel mixing rates to create fuel-rich reducing zones and extracting heat to reduce final oxidation temperatures.

To avoid the need for costly post-combustion NO_x removal, several in-furnace NO_x control strategies have been developed and applied to boilers. These include reduced air preheat, load reduction, low excess air, flue gas recirculation, overfire air, deep air staging, fuel staging (or reburning), and various low-NO_x burner systems. While NO_x emissions can be reduced by 20-80 percent using these technologies, from uncontrolled levels exceeding 1,000 ppm for some high nitrogen content coals, the application of these combustion modifications can reduce combustion efficiency and increase sooting and slagging in the boiler. These problems are of particular concern in the boiler cofiring of fuels and wastes where high waste destruction efficiencies and minimal formation of other incomplete combustion products are of paramount importance. Furthermore, practical constraints, such as burner and boiler sizes, limit the effectiveness of NO_x control by combustion modification.

EPA is currently involved in the development and field demonstration of two evolving NO_x control technologies: the precombustion chamber burner and reburning (fuel staging). These combustion modification strategies provide alternatives to expensive post-combustion NO_x removal technologies, such as selective catalytic reduction which is being utilized extensively in Japan and West Germany, for achieving low NO_x emissions when firing high nitrogen content fuels or incinerating highly nitrated wastes. The goal of this work was to utilize the precombustion chamber burner and air or air/fuel staging concepts to develop a burner that is practical for both new and retrofit installations and is capable of

burning high nitrogen fuel/waste streams with low NO_x emissions and high combustion efficiency. Specifically, a NO_x emission of less than 0.2 lb (as NO_2)/10^6 Btu (or approximately 175 ppm NO_x, measured dry at 0 percent O_2) for firing gaseous and liquid fuels doped with up to 5 percent nitrogen (by weight) was targeted (1 lb/10^6 Btu = 0.43 kg/GJ).

This study was carried out in three phases. The first phase of this study dealt with a fundamental exploration of post-flame combustion technology, known as reburning. In this phase the fundamentals of reburning and its suitability to combustion applications were studied in detail. The findings of this study, which lasted from March 1983 to October 1984, are documented by Mulholland et al.[5]

The burner used during the first phase of the study was a low NO_x precombustion chamber burner, designed and fabricated under an EPA contract by Energy and Environmental Research Corporation (EERC), Irvine, California. The burner proved to be a useful research tool, though its practicality was limited because of its size and cost. As a follow-on of the reburning work, the burner was reduced in size from 600 ms to 350 ms first-stage residence time. Subsequent proof-of-concept tests involving the reduced size precombustion chamber low NO_x burner and air or air/fuel staging were carried out. The proof-of-concept tests in this second phase helped to generate the experimental matrix for the third phase.

During the third phase of the study a vertical downfired combustor was designed, fabricated, and installed. It was of a modular design to allow residence time variations, and was capable of firing gaseous or liquid fuels. It had ports for detailed samplings and variable fuels and air injection locations/methods. Parametric tests were carried out using this new burner to rigorously test and prove the concepts generated in the second phase.

This report covers the project activities in the period November 1984 to July 1987. Much of the information in this report is documented in various technical presentations and papers, which are tabulated in Table 1-1.[5]

TABLE 1-1. TECHNICAL PRESENTATIONS AND PAPERS

Period	Description
April 83-April 84	"Application of Reburning for NO_x Control to a Firetube Package Boiler," J.A. Mulholland and W.S. Lanier, Journal of Engineering for Gas Turbines and Power, Vol. 107, July 1985. Presented at the Joint Power Generation Conference, Toronto, Ontario, Canada, Sept. 30-Oct. 4, 1984
May 84-Jan 85	"The Effect of Fuel Nitrogen in Reburning Application to a Firetube Package Reboiler," J.A. Mulholland and R.E. Hall, 1985 Joint Symposium on Stationary Combustion NO_x Control, Boston, Massachusetts, May 6-9, 1985
May 84-Jan 85	"Fuel Oil Reburning Application for NO_x Control to Firetube Package Boilers," J.A. Mulholland and R.E. Hall, Journal of Engineering for Gas Turbines and Power, Vol. 109, pp. 207-214 (April 1987). Presented at the Joint Power Generation Conference, Milwaukee, Wisconsin, Oct. 20-24, 1985.
April 83-April 84	"Reburning Thermal and Chemical Processes in a Two-Dimensional Pilot-Scale System," W.S. Lanier, J.A. Mulholland, and J.T. Beard, Twenty-First Symposium (International) on Combustion, Munich, West Germany, Aug. 3-8, 1986
April 83-Aug 85	Reburning Application to Firetube Package Boilers, J.A. Mulholland, E.E. Stephenson, C. Pendergraph and J.V. Ryan, EPA Final Report, EPA-600/7-87-011 (NTIS PB87-177515), March 1987
Nov 85-May 86	"A Multistaged Burner Design for In-Furnace NO_x Control," J.A. Mulholland and R.K. Srivastava. Presented at the Joint Power Generation Conference, Portland, Oregon, Oct. 19-23, 1986
June 86-Jan 87	"Pilot-Scale Tests of a Multistaged Burner Designed for Low NO_x Emission and High Combustion Efficiency," J.A. Mulholland and R.K. Srivastava. Presented at EPA/EPRI Joint NO_x Symposium, March 23-26, 1987, New Orleans, Louisiana.
June 86-Jan 87	"A Multistaged Approach for In-Furnace NO_x Control," R.K. Srivastava and J.A. Mulholland. Presented at the AIChE Spring 1987 National Meeting, Houston, Texas, March 1987.
June 86-Jan 87	"Low NO_x, High Efficiency Multistaged Burner: Gaseous Fuel Results," R.K. Srivastava and J.A. Mulholland, Environmental Progress, Vol. 7, No. 1, pp. 63-70 (April 1987).
June 86-Mar 87	"Low NO_x, High Efficiency Multistaged Burner: Fuel Oil Results," J.A. Mulholland and R.K. Srivastava. Presented at the 80th Air Pollution Control Association Annual Meeting and Exhibition, New York, NY, June 21-26, 1987, and submitted for publication in Journal of the Air Pollution Control Association.

(continued)

TABLE 1-1. TECHNICAL PRESENTATIONS AND PAPERS (concluded)

Period	Description
Presentations	
Dec 6 and 7, 1983	EPA/ASME/APCA Technical Information Exchange, Research Triangle Park, NC
Jan 25 and 26, 1984	EPA Reburning Review and Coordination Panel Meeting, Salt Lake City, Utah
Mar 28, 1985	EPA Reburning Review and Coordination Panel Meeting, Salt Lake City, Utah

SECTION 2

EXPERIMENTAL FACILITY

The major components of the pilot-scale experimental facility used in this study consisted of a precombustion chamber burner; a package boiler simulator (PBS); air/fuel/dopant flow systems; a burner management/safety system; and combustion gas temperature and sample measurement systems. These components, located in Wing G High Bay area of EPA/ERC, are now described in detail.

2.1 PRECOMBUSTION CHAMBER BURNER

The precombustion chamber burner uses a staged combustion technology capable of achieving a NO_x emission of less than 0.1 lb (as NO_2)/10^6 Btu (or approximately 90 ppm NO_x), even with high nitrogen content fuel firing.[6] It consists of a primary air and fuel injection system, a large refractory wall precombustion chamber, and a secondary air injection section. Fuel and primary air are injected, for rapid mixing, into the nearly adiabatic precombustion chamber to effect a first-stage stoichiometry between 0.6 and 0.8. A residence time between 0.6 and 1.0 s allows maximum reduction and conversion of fuel nitrogen species to N_2 in the fuel-rich precombustion chamber. First-stage combustion gas products exit the burner through a convergent section that minimizes both radiative heat loss to the boiler and backmixing of the secondary air. The transition section between the burner and boiler is water-cooled to reduce combustion gas temperatures before final air addition.

The precombustion chamber burner has been tested on a full-scale (16 MW) crude-oil-fired steam generator used for thermally enhanced oil recovery (TEOR) in Kern County, CA.[7] A 30-day continuous monitoring test demonstrated the burner's ability to maintain a nominal NO_x emission of 70 ppm and a high combustion efficiency. During burner optimization testing, NO_x, CO, and smoke emissions were measured over a range of first-stage stoichiometries. These data indicate the sensitivity of NO_x emission to first-stage stoichiometry and the good hydrocarbon burnout characteristics of the

burner. Earlier pilot-scale tests firing nitrogen-free fuels suggest that the minimum NO_x level of about 50 ppm can be attributed to second-stage thermal NO_x formation.

A test designed to demonstrate the potential use of this burner for nitrogenous waste incineration was performed at EPA's Air and Energy Engineering Research Laboratory. A pilot-scale (0.6 MW) precombustion chamber burner was used to incinerate a surrogate nitrogenous waste mixture of 9.1 percent (by volume) pyridine in fuel oil. A NO_x emission of less than 100 ppm was maintained, with greater than 99.99999 percent destruction of the pyridine. The relative NO_x emissions, with and without pyridine addition, indicated that less than 1 percent of the fuel nitrogen was converted to NO. This preliminary result sparked interest in utilizing the precombustion chamber burner for low NO_x, high efficiency combustion.

However, while the precombustion chamber burner has been demonstrated successfully in pilot-scale and field tests, its large size makes it impractical for most boiler retrofit applications. Reducing the burner size results in a first-stage residence time that is insufficient to fully convert the fuel nitrogen to N_2; hence, higher NO_x emissions result. More NO_x control can be achieved by further staging of the combustion process in the boiler.

For this study, during Phases 1 and 2 the 0.6 MW precombustion chamber burner, designed by the Energy and Environmental Research Corporation of Irvine, California, was used. This burner is shown in Figure 2-1.

The burner consisted of primary fuel and primary air injectors, two 0.51 m diameter by 0.91 m long spool modules, and one 0.25 m diameter transition section with eight radial ports for secondary air addition. To achieve rapid mixing in the precombustor, the primary fuel was injected through a divergent nozzle. The primary air, which was not preheated, passed through fixed swirl vanes. These burner sections were lined with a thick refractory wall to minimize heat loss and maintain high temperatures that promote conversion of fuel nitrogen to N_2 under fuel-rich stoichiometries. The reduction of burner diameter to 0.25 m in the transition section minimized radiative loss to the boiler and prevented backmixing of combustion gases, thus allowing precise control over burner stoichiometry.

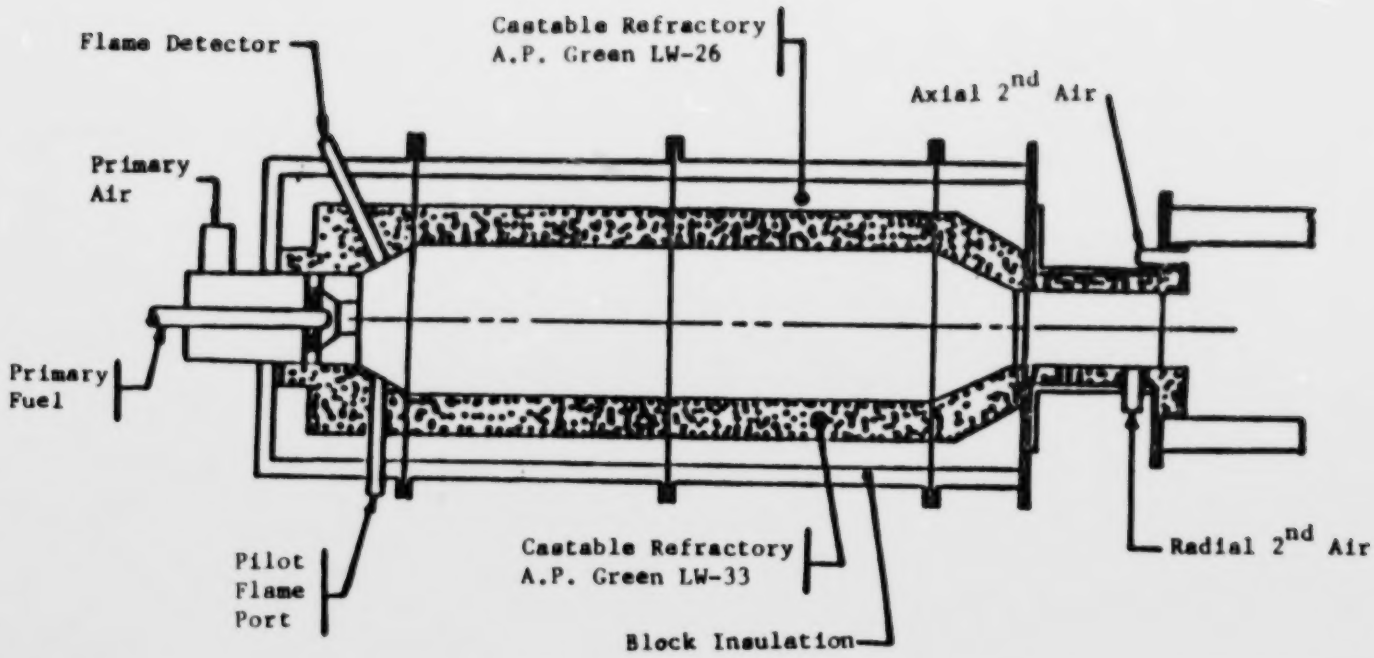


Figure 2-1. Horizontal low NO_x precombustion chamber burner.

The burner was designed for substoichiometric (fuel-rich) operation, requiring secondary combustion air for complete burnout of primary fuel. This air was provided through the radial injection ports in the transition section, shown in Figure 2-2. The transition section was water-cooled so that the combustion gas was cooled before secondary air addition, minimizing thermal NO generation. Primary fuel nitrogen was simulated by doping ammonia (NH_3) into natural gas or pyridine (C_5H_5N) into distillate fuel oil.

For Phase 2 proof-of-concept tests, the precombustion chamber burner was shortened by removing one of the two spool modules. This shorter burner, shown in Figure 2-3, had a first-stage combustion gas residence time of 350 ms at a nominal load of 2×10^6 Btu/h (0.6 MW).

For Phase 3 tests, a versatile precombustion chamber burner developed by Acurex Corporation was used. This burner, shown in Figure 2-4, was vertical, modular (with up to four spool modules), and had ports for observation, sampling, and air/fuel injections. This burner had all the features of the Phase 2 precombustion chamber burner. In addition, its modular construction provided variations of residence time, and it had air/fuel staging, sampling, and observation capabilities implicit in its design. Specifically, during the Phase 3 testing, the shortest configuration of the burner (including the burner module and the elbow module) was used, with a first-stage residence time of 250 ms at nominal load.

2.2 FIRETUBE PACKAGE BOILER SIMULATOR (PBS)

The firetube package boiler simulator (PBS) used in this study was manufactured by Dynamic Sciences, Inc., in 1972. The PBS has a nominal rated capacity of 1.0 MW (3.5×10^6 Btu/h) and can be fired with natural gas, distillate oil, or residual oil. As seen in Figure 2-5, the radiant section is a double-walled circular cylinder of 2.3 m (7.5 ft) length and 0.6 m (2.0 ft) internal diameter. A 90° elbow section directs gas flow to the vertical stack. An induced draft fan can be used to pull gases through a horizontal convective section (shell and tube heat exchanger) and to return the gases to the stack. The convective section was not used in this study because all relevant chemistry is effectively frozen at the radiant section exit temperature.

The radiant section is cooled with Dowtherm G heat transfer fluid, with a heat extraction rate and wall temperatures similar to those found in commercial firetube package boilers. The Dowtherm system,

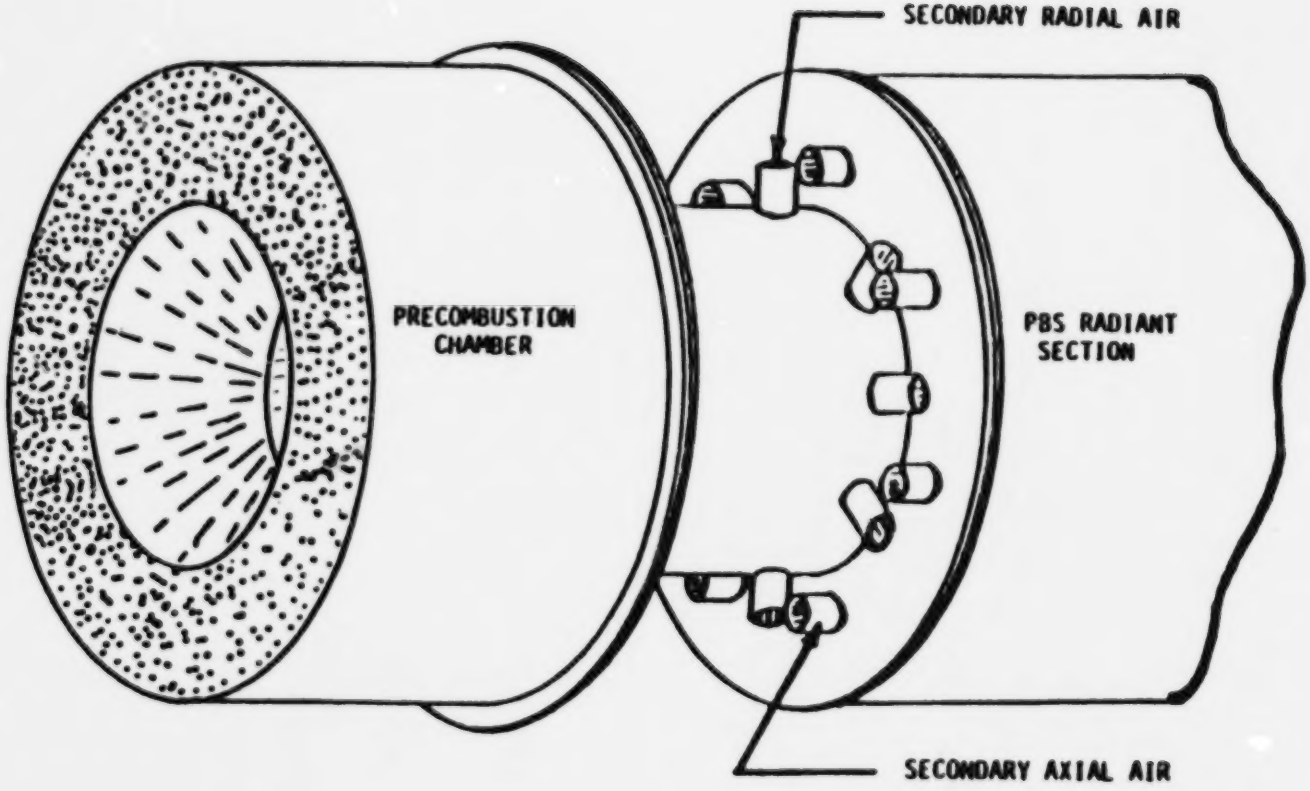


Figure 2-2. Burner/boiler transition section.

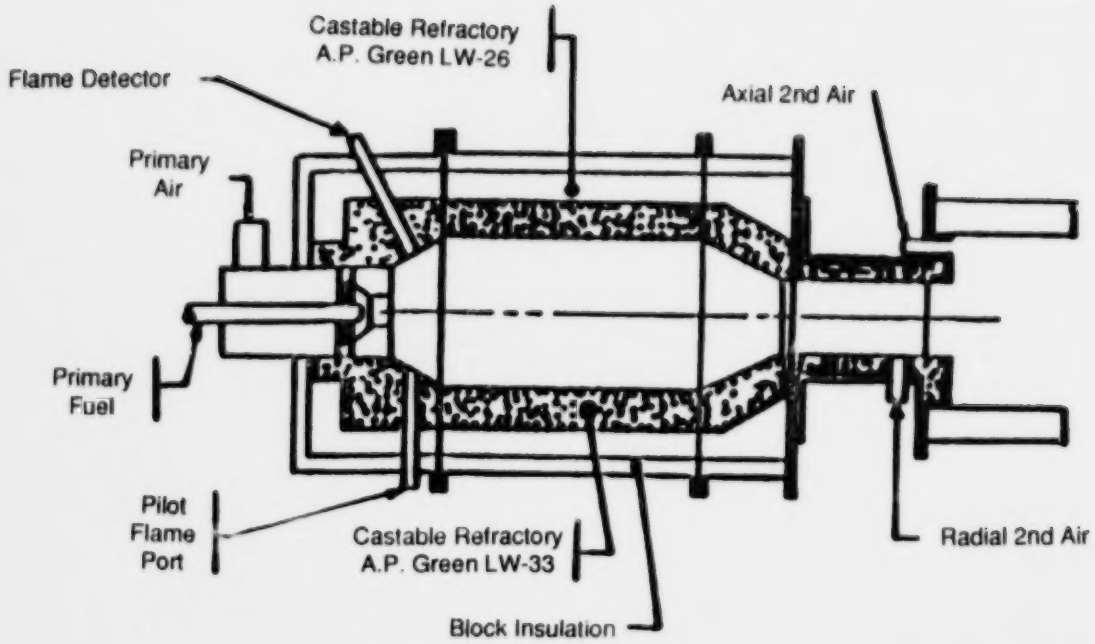


Figure 2-3. Reduced size low NO_x precombustion chamber burner.

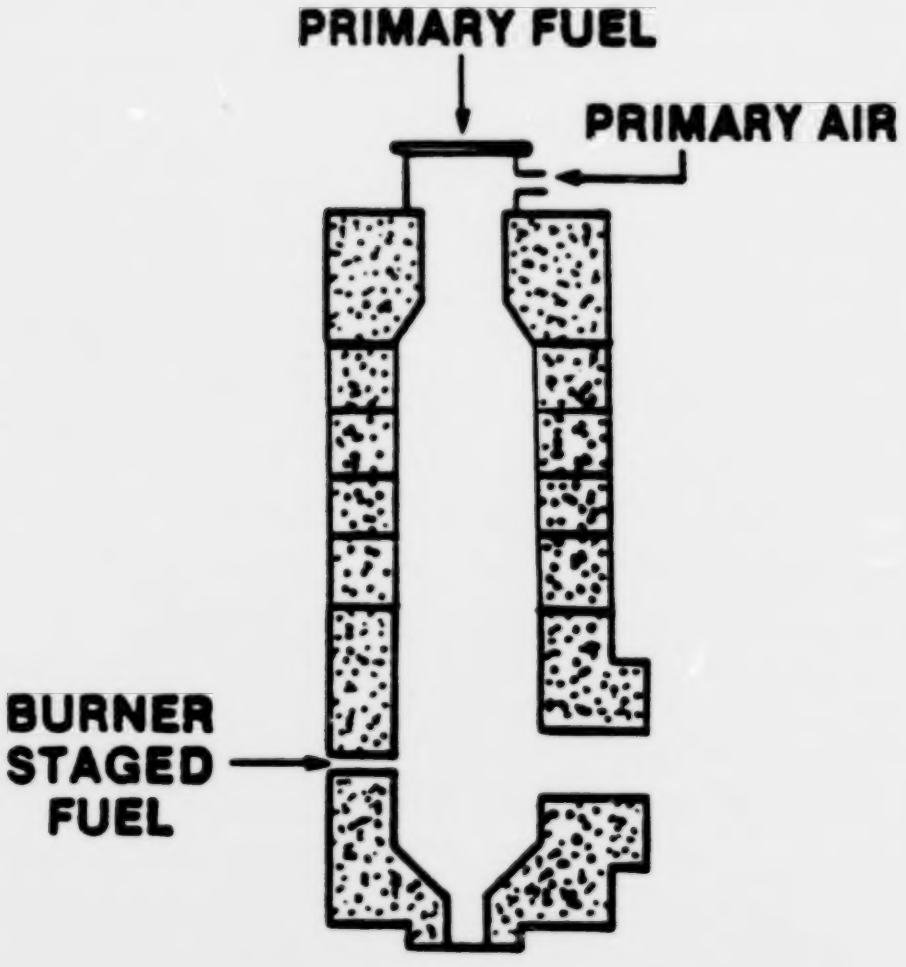


Figure 2-4. Vertical, modular, low NO_x precombustion chamber burner.

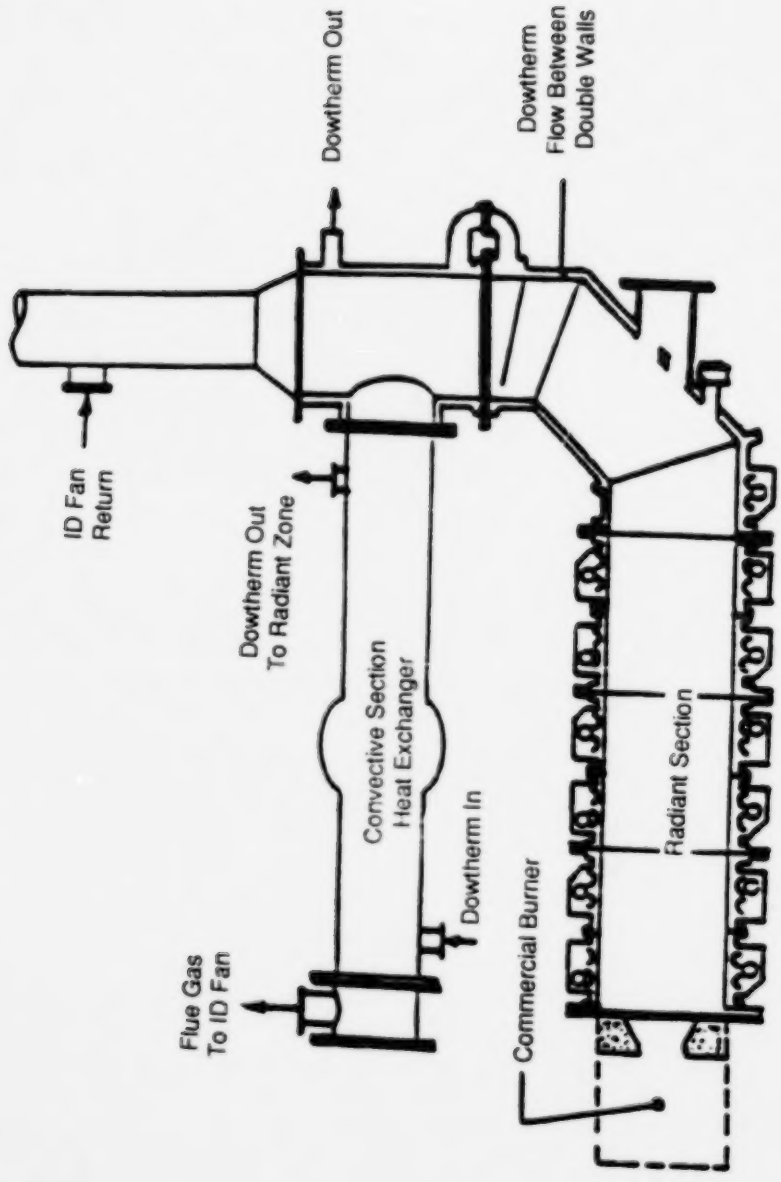


Figure 2-5. Package boiler simulator.

which dumps its heat to a cooling tower through a house industrial water system, precludes problems associated with raising and disposing of steam. Wall penetrations (originally used in staged combustion studies) at 0.25 m (10 in), 0.51 m (20 in), 1.0 m (40 in), and 1.3 m (50 in) from the firetube front face were useful as test ports for the insertion of in-flame sampling probes and reburn fuel injectors. In addition, the end plate of the boiler has a port for injection of deep-staged air or reburning fuel. The boiler's front face has eight axial ports for the addition of staged air in Phase 1 tests. For Phase 2 and Phase 3 tests, two of the eight axial air ports on the PBS were modified to provide ports for staging fuel into the boiler at an angle of 45°. This design allowed reburning application from the boiler front face, with aerodynamic separation of the fuel-lean and fuel-rich zones in the boiler.

The combination of secondary air additions through radial and axial ports in the transition section and the boiler front face, respectively, facilitates the production of a continuous series of secondary flames, from a short radial flame (all radial secondary air) to a long axial flame (all axial secondary air.

2.3 COMBUSTION AIR/FUEL/DOPANT FLOW SYSTEMS

As seen in Figure 2-6, primary and secondary combustion airs were supplied by a single blower powered by an 11 kW (15 hp) electric motor. A Meriam laminar flow element (LFE) monitored total air flow. Primary air, secondary radial air, and secondary axial air were monitored by venturi flow meters. All pressure differentials were measured with fluid manometers. A small amount of the primary combustion air was bled across the flame detector to prevent condensation on its lens. The inlet static pressures and temperatures of the flow devices were monitored with Magnehelic pressure gauges and bimetal thermometers to correct flows to standard conditions (1 atm, 70 °F or 101.3 kPa, 21 °C). All air flow devices were calibrated against an in-house standard LFE.

Final (burnout) combustion air was supplied by the house compressed air system, as is shown in Figure 2-6. The compressor output was regulated to a pressure of approximately 90 psig (620.6 kPa) and the air flow was measured by a venturi meter with a U-tube manometer.

Figure 2-7 shows the natural gas supply system. The main burner natural gas flow was measured with an orifice plate and an inclined manometer. House gas pressure was regulated to a nominal 5 psig (34.5 kPa). The gas flow split after the orifice, with one leg going to the main burner and

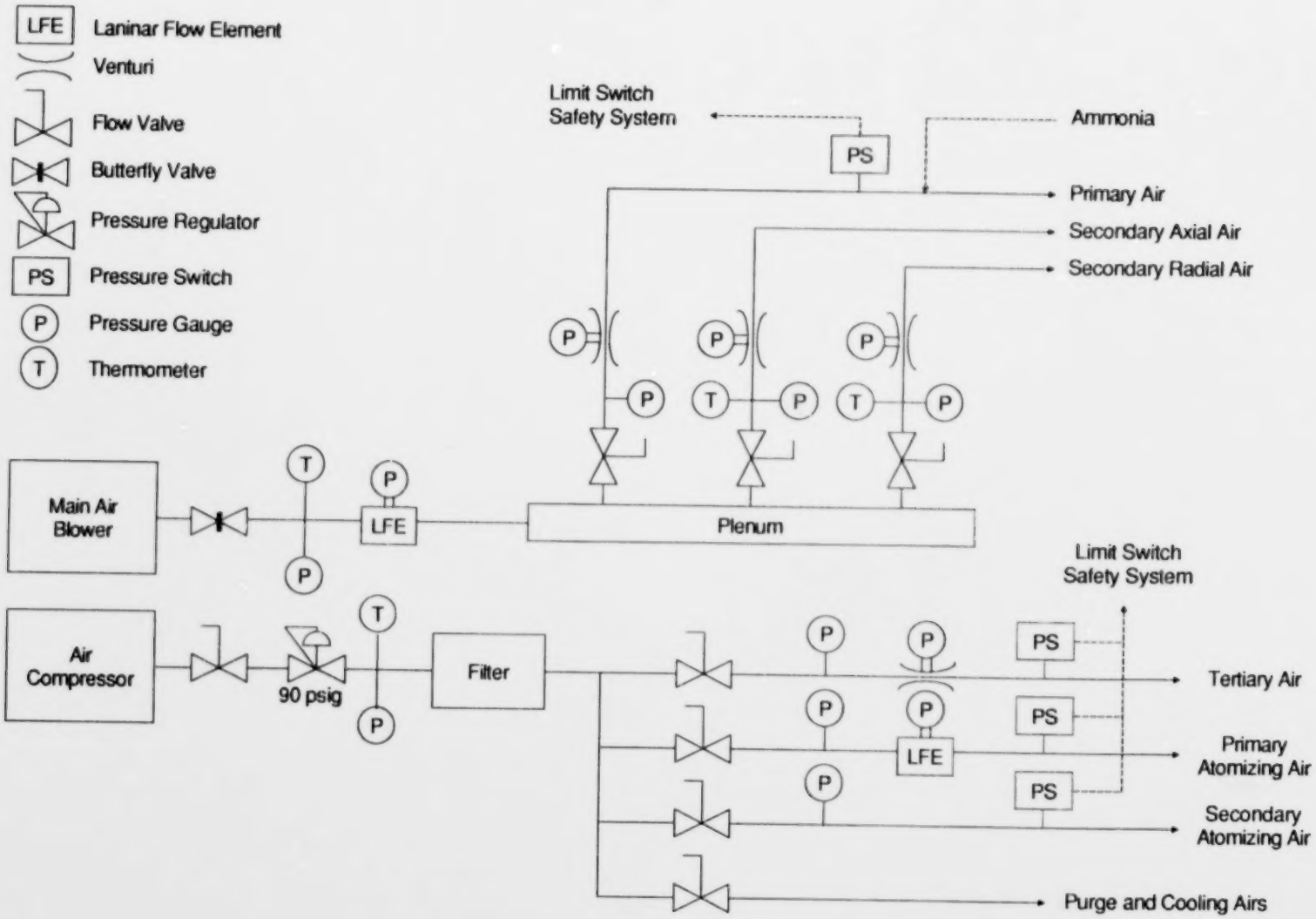


Figure 2-6. Combustion air supply system diagram.

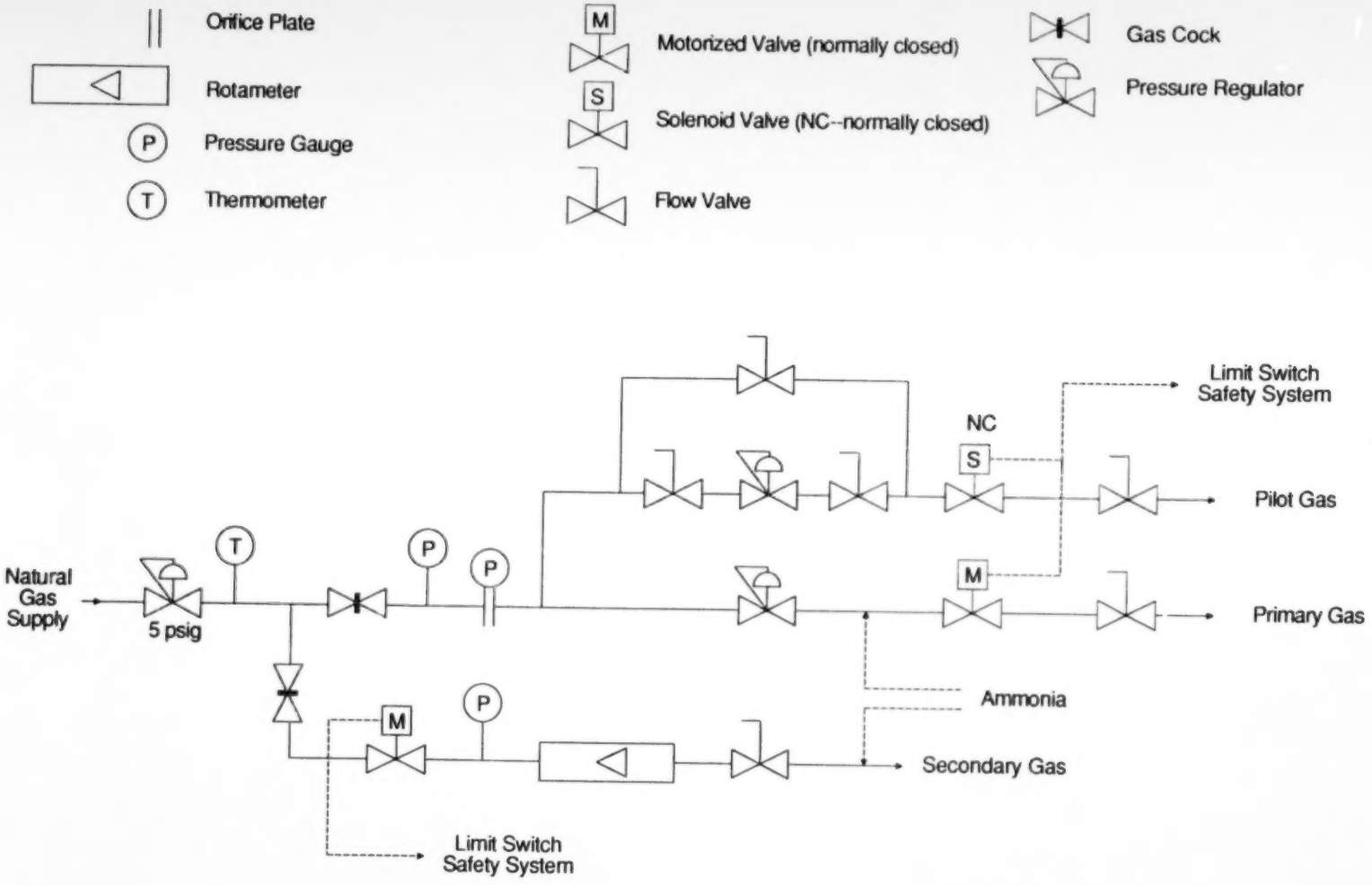


Figure 2-7. Natural gas supply system diagram.

another to a pilot torch. Normally closed solenoid valves were electrically tied to the burner management/safety system, allowing fuel flow only after a series of flame safeguards and limit switches were actuated. The primary burner gas pressure was further regulated before passing through a normally closed, motorized valve (actuated by the burner management/safety system) and a manual gas cock. The gas cock and the diameter of the holes in the gas nozzle regulated the gas flow. Six holes were drilled symmetrically around the gas nozzle centerline, at a 30° angle to the centerline axis. Several nozzles with varying diameter holes were used to control gas flow to appropriate levels during burner operation. Table 2-1 presents the results from fuel analyses performed on this fuel.

The fuel oil system is shown in Figure 2-8. The circuit included solenoid valves which were tied to the burner management/safety system, allowing oil flow only after a series of flame safeguards and

TABLE 2-1. FUEL ANALYSES

Natural Gas

Analysis	Natural Gas
Higher Heating Value	
(Btu/cubic ft, @ 60°F, 14.73 psig)	1031.6
(Btu/lb$_f$)	23,563
Encal Chromatograph Analysis (mol %)	
Nitrogen	0.35563
Carbon Dioxide	0.91649
Methane	96.11870
Ethane	1.85666
Propane	0.38608
I-Butane	0.09849
N-Butane	0.10139
I-Pentane	0.04272
N-Pentane	0.02865
Hexanes Plus	0.09515
Specific Gravity (@ 60 °F, 14.73 psig, air = 1.0)	0.58480
Theoretical Air	
(mol air/mol fuel)	9.69
(lb$_a$/lb$_f$ or kg$_a$/kg$_f$)	16.6
(lb$_a$/10,000 Btu)	7.04

a air
f fuel

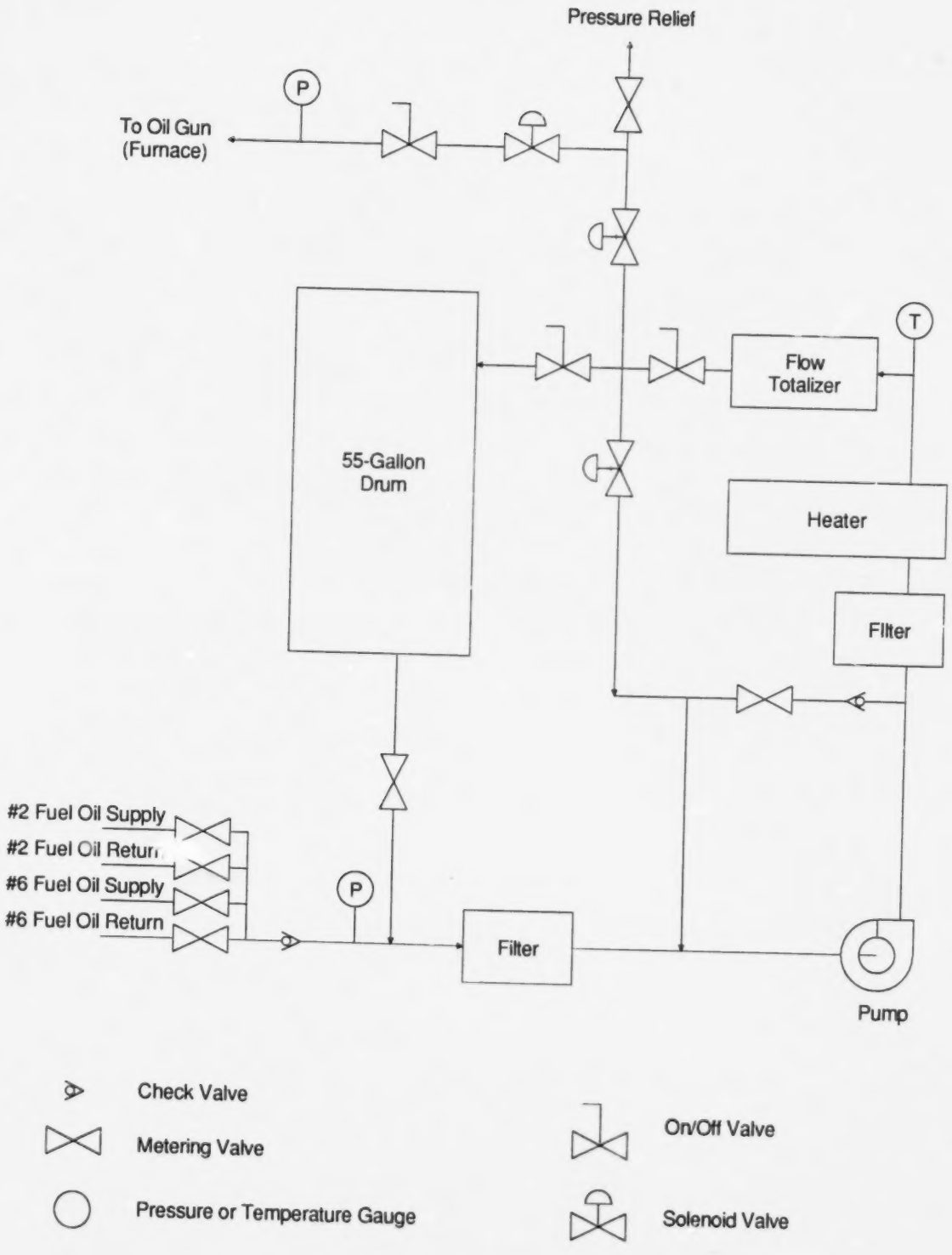


Figure 2-8. Fuel oil supply system diagram.

limit switches were actuated. The oil flow was metered by the metering valve, located near the 55 gallon (0.21 m^3) drum, and the flow was measured by the flow totalizer. The fuel oil feed circuit included a recirculation loop.

Ammonia could be supplied to the precombustion chamber burner fuel flow to regulate primary NO_x concentration independent of other primary burner parameters. The supply system is shown in Figure 2-9. The ammonia flow, which was supplied from cylinders regulated to a nominal pressure of 10 psig, was controlled by a precision needle valve and monitored by a rotameter designed for ammonia service. For natural gas firing, ammonia was doped into the fuel line sufficiently upstream to ensure complete mixing prior to injection.

The natural gas secondary fuel supply was tapped from the house natural gas supply system, as shown in Figure 2-7. The fuel flow was metered by a rotameter designed for natural gas service. Ammonia could be doped into the secondary natural gas to simulate fuel-bound nitrogen. This flow was metered, as shown in Figure 2-9.

2.4 BURNER MANAGEMENT/SAFETY SYSTEM

A burner management/safety system, built by the North American Manufacturing Company, was used to permit safe and consistent operation of the facility. The central feature of the system is a cam-driven programmer tied to an ultraviolet flame detector. Depending on which fuel is being fired, a series of safety interlocks must be made to initiate the starter sequence. These include initial and continuous checks on primary combustion air flow; atomizing air flow (oil fired only); Dowtherm temperature and flow; and water coolant flow (to burner head, transition section, and PBS end plate). A control system logic diagram is shown in Figure 2-10. With all interlocks made, the combustion air blower will prepurge the combustor for 1 min. After this prepurge period, the pilot torch solenoid valve is actuated for 15 s, during which time the pilot torch is manually lighted, inserted into the combustor, and detected by the UV flame detector. Then, the main fuel valves are automatically actuated. The pilot flame remains on for 5 s, during which time the main flame must be lighted. If it is not lighted, the main fuel valves are de-energized and the combustor is purged for 30 s. The safety system provided automatic shutdown in the event of a safety check failure.

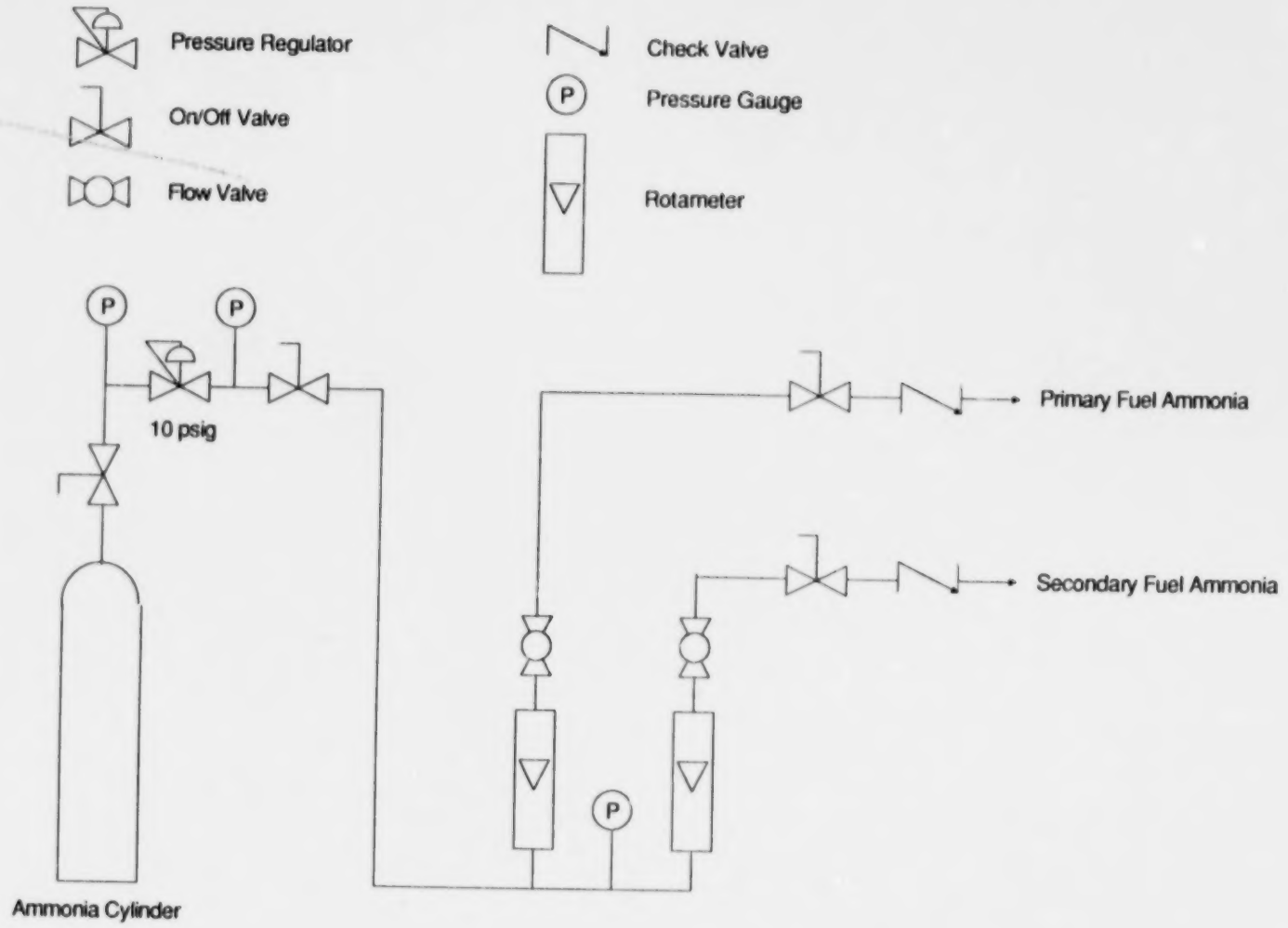


Figure 2-9. Ammonia supply system diagram.

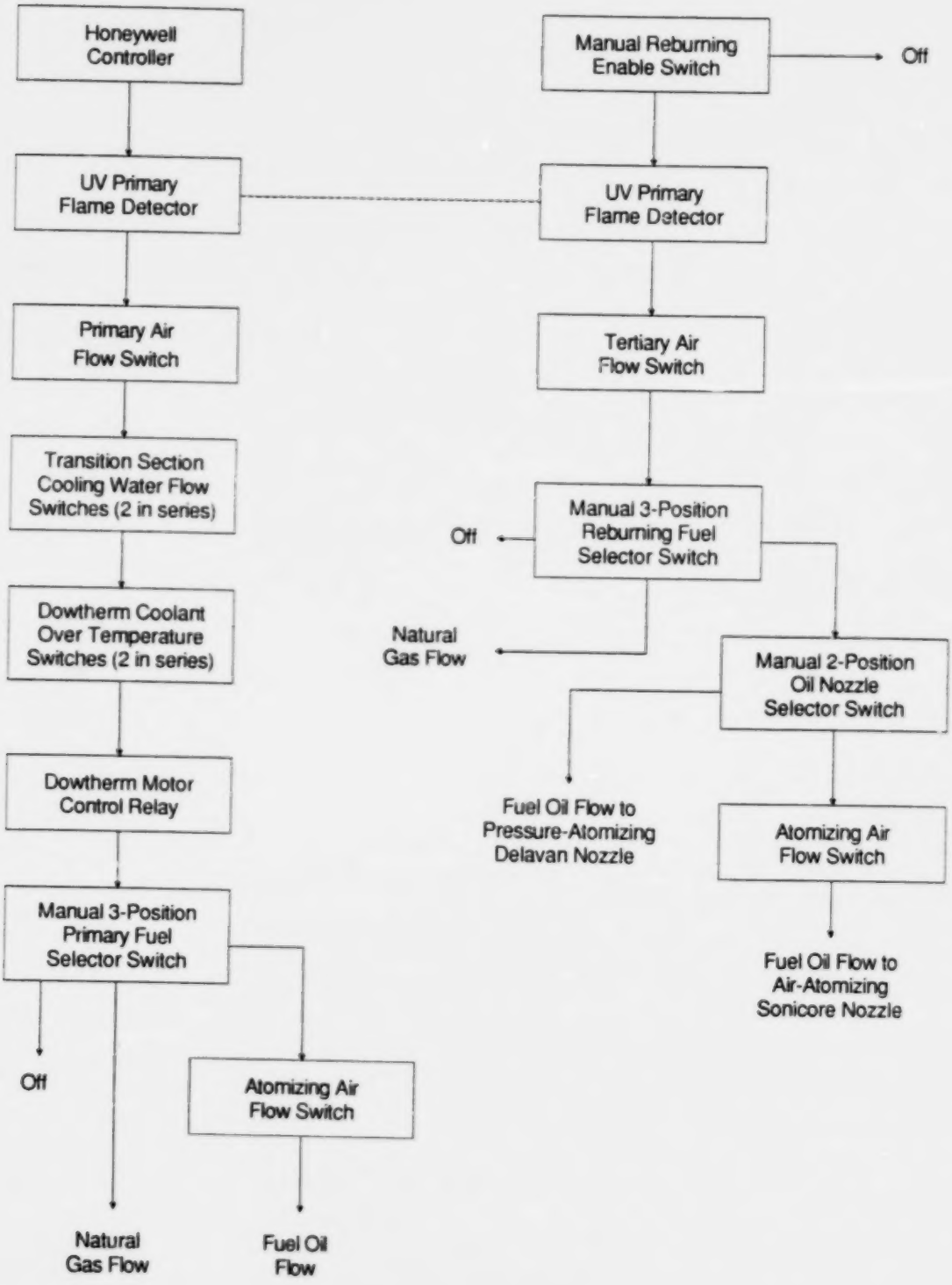

Honeywell Controller
UV Primary Flame Detector
Primary Air Flow Switch
Transition Section Cooling Water Flow Switches (2 in series)
Dowtherm Coolant Over Temperature Switches (2 in series)
Dowtherm Motor Control Relay
Manual 3-Position Primary Fuel Selector Switch
Off
Natural Gas Flow
Atomizing Air Flow Switch
Fuel Oil Flow
Manual Reburning Enable Switch
Off
UV Primary Flame Detector
Tertiary Air Flow Switch
Manual 3-Position Reburning Fuel Selector Switch
Off
Natural Gas Flow
Manual 2-Position Oil Nozzle Selector Switch
Fuel Oil Flow to Pressure-Atomizing Delavan Nozzle
Atomizing Air Flow Switch
Fuel Oil Flow to Air-Atomizing Sonicore Nozzle

Figure 2-10. Burner management system logic diagram.

2.5 STACK GAS SPECIATION

The PBS stack contained both a thermocouple probe and a sampling probe. The sampling probe drew a sample through a porous metal filter, pulling from the entire cross-section of the stack. The stack effluent was sampled and analyzed by a Continuous Emissions Monitoring System (CEMS), shown in Figure 2-11. The combustion gas sample was extracted through a porous metal filter inserted across the stack cross-section. Transported in stainless steel and Teflon tubing, the sample gas passed through a Hankerson dryer and a particulate filter. The sample gas was then split, allowing a portion of the flow to pass through a Dryrite canister for further drying before going to the individual analyzers for oxygen, total unburned hydrocarbon, carbon dioxide, and carbon monoxide. The rest of the sample went directly to the NO_x analyzer, bypassing the NO_x absorbing Dryrite material.

The NO_x meter is a Thermo-Electron Model 10A analyzer which operates via chemiluminescence. A small portion of the sample flow to the instrument is metered into a vacuum (reaction) chamber where it is allowed contact with an excess of ozone from an integral ozonator. Nitric oxide (NO) and ozone (O_3) react to form N_2O, a portion (approximately 10 percent at room temperature) of which is elevated to an excited state. The excited molecules return to ground state and give off light of a characteristic frequency. This light is detected by a photomultiplier tube. The output is amplified and scaled to read directly in parts per million. The NO/NO_x analyzer has a range of 0-1,000 ppm. A high purity N_2 and a gas of known NO concentration were used to calibrate this instrument.

For the conditions sampled in the firetube package boiler, nearly all of the NO_x was in the form of NO and, therefore, the NO_x analyzer was operated in the NO measurement mode.

The O_2 meter was a Beckman Model F3 Oxygen Analyzer, which operates by utilizing the paramagnetic property of oxygen. Other gases present in significant concentration in the stack effluent do not exhibit this property. The instrument was calibrated with high purity N_2 and room air. Its measurement range is 0-25 percent.

The CO_2 and CO monitors used were Beckman Series 864/865 Infrared Analyzers. They operate by directing identical infrared beams through a sample cell and a sealed reference cell. The difference between the strength of the beams, as measured by a detector at the opposite end of the cell,

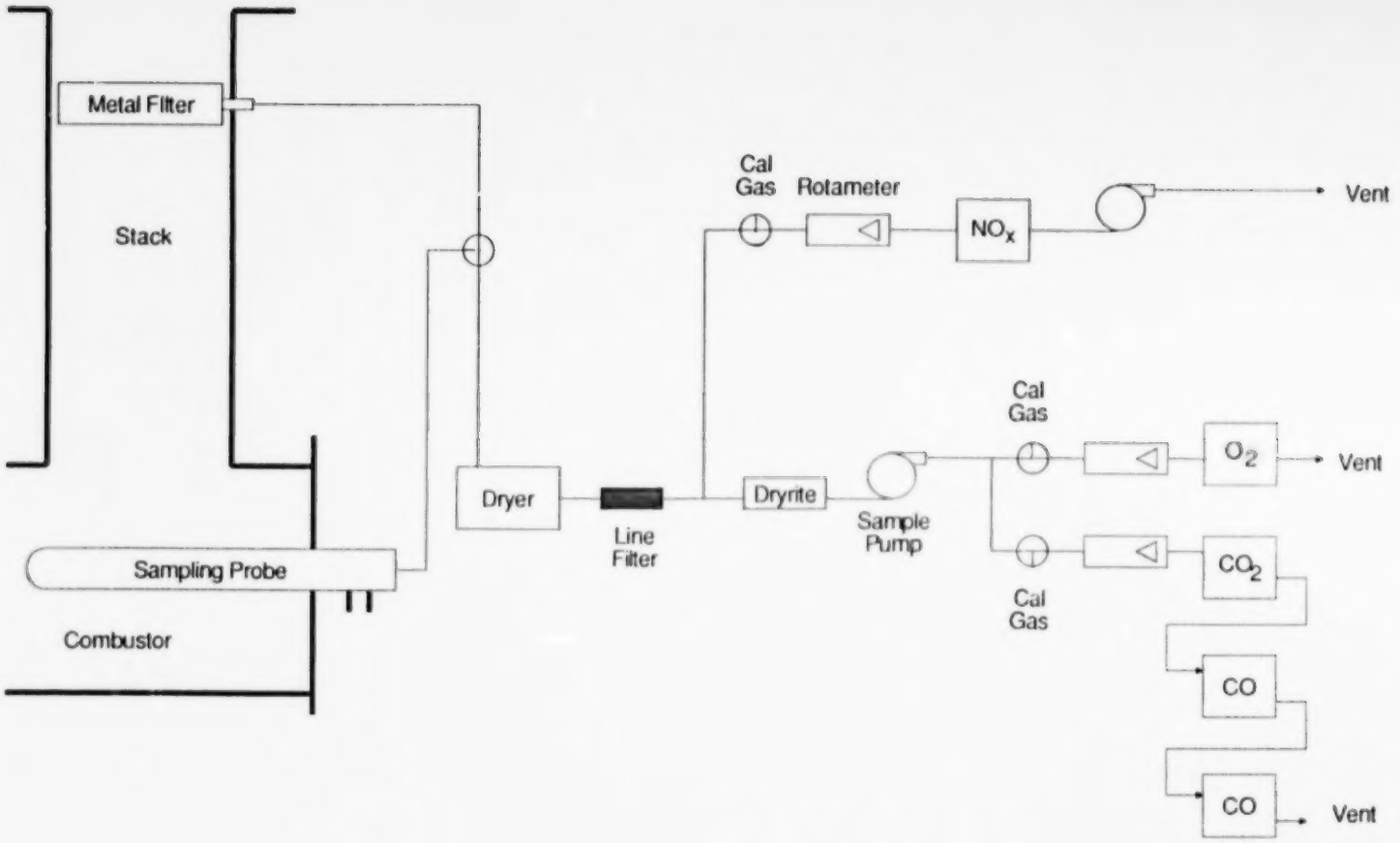


Figure 2-11. Continuous emissions monitoring system (CEMS) diagram.

is proportional to the concentration of the target compound in the sample. Calibration was accomplished with a high purity N_2 gas and a known concentration sample of the target gas. The range of the CO_2 analyzer is 0-20 percent. The range of the first of two CO monitors, used for stack gas measurement, is 0-2,000 ppm. The second CO monitor, used for in-flame measurements, has a range from 0-5 percent.

The gaseous emission monitor specifications are summarized in Table 2-2.

2.6 TEMPERATURE MEASUREMENTS USING A SUCTION PYROMETER

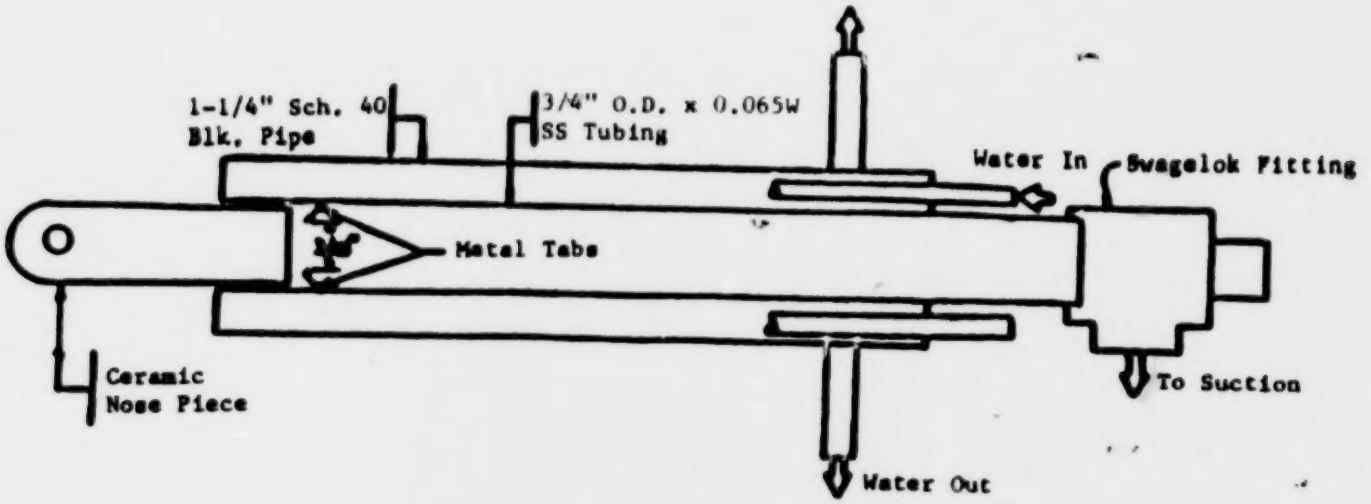
The suction pyrometer designed for in-flame temperature measurement in the furnace was a 1.0 m (3.3 ft) long probe. The basic design of the suction pyrometer is shown in Figure 2-12. Platinum and platinum/13 percent rhodium 10 mil (0.254 mm diameter) thermocouple wire was fed through a two-hole alumina tube and welded to form an R-type thermocouple junction. The thermocouple was slipped inside a 0.635 cm (0.25 in) diameter alumina tube with a closed end for radiation shielding. To complete the suction pyrometer, the shielded R-type thermocouple was slipped into the water-cooled probe assembly. The thermocouple tip extended 15 cm (6 in) past the end of the water-cooled probe, inside a close-end alumina nosepiece with a 0.635 cm (0.25 in) hole near its tip (see Figure 2-11).

Suction for the pyrometer was provided by a carbon vane pump; the flow rate was monitored by a dry gas meter. The pump and the meter were protected from moisture by an EPA Method 5 condensation train consisting of two impingers and a silica gel trap in an ice bath.

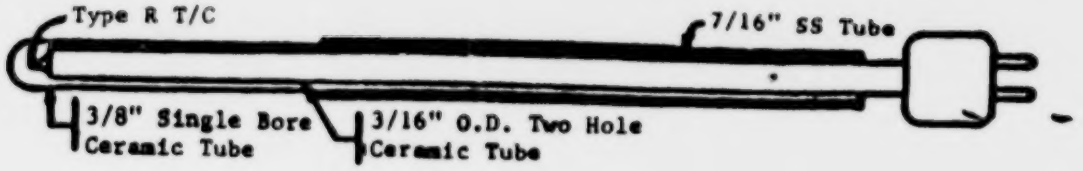
Thermocouple output was read by an Omega Model 2166A digital thermometer. When in operation, hot combustion gases were pulled at a high velocity through the nosepiece port and down the annulus between the nosepiece and the shielded thermocouple. As the gas flow rate across the shielded thermocouple increased, convective heat transfer to the thermocouple tip predominated over radiative transfer to the cold boiler walls, and the actual gas temperature was approached. Figure 2-13 shows that at flow rates in excess of 110 L/min, asymptotic operation and, therefore, actual gas temperature indication was approached by the suction pyrometer. The construction of the suction pyrometer allowed temperature measurement up to approximately 2,000 K (3,140 °F).

TABLE 2-2. GASEOUS EMISSION MONITOR SPECIFICATIONS

Gas	Sample Type	Instrument Type	Manufacturer/ Model	Range
O_2	Continuous	Paramagnetic	Beckman/F3	0 to 5, 10, 25%
CO_2	Continuous	Infrared	Beckman/864	0 to 5, 10, 20%
CO	Continuous	Infrared	Beckman/865	0 to 500, 1,000, 2,000 ppm
NO	Continuous	Chemiluminescence	Teco/10A	0 to 2.5, 10, 25, 100, 250, 1,000, 2,500, 10,000 ppm



Part B. Water Cooled Probe Assembly



Part A. Shielded Thermocouple

Figure 2-12. Suction pyrometer design.

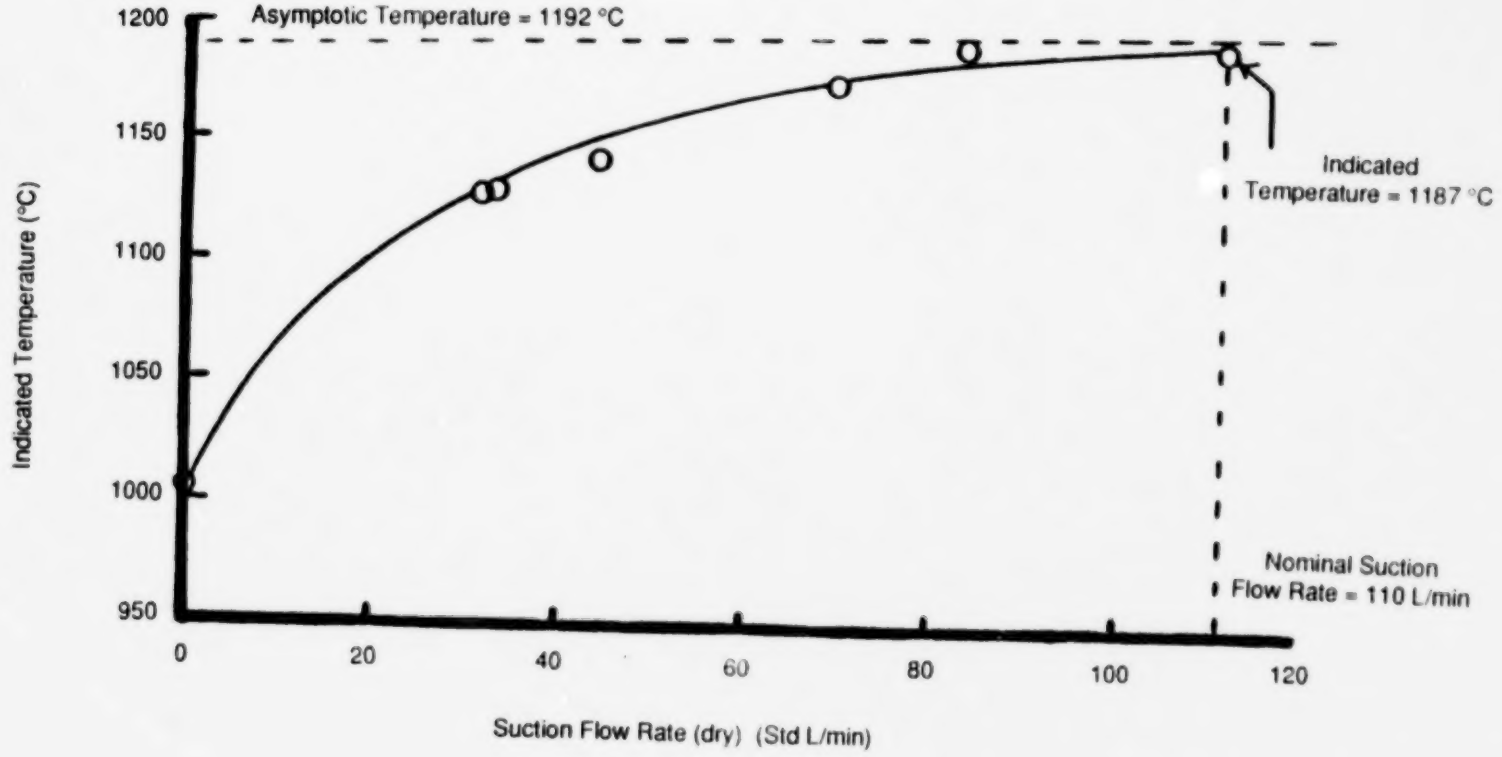


Figure 2-13. Suction pyrometer calibration curve.

SECTION 3

PROOF-OF-CONCEPT TESTS

3.1 BACKGROUND

While the precombustion chamber burner, discussed in Section 2, has been demonstrated to achieve low NO_x levels for high nitrogen fuels, its large size makes it impractical for many boiler applications. Reducing the burner size results in incomplete reduction of the fuel nitrogen in the precombustion chamber and, hence, higher NO_x emissions. However, an in-furnace NO_x control technology exists for removing NO_x from the combustion gas stream. NO_x formed in the primary flame can be destroyed by fuel staging, or reburning. By diverting portions of the fuel and combustion air streams from the main burner(s) for injection into the post-flame gases, reburning establishes a three-stage combustion process consisting of a fuel-lean primary zone, a fuel-rich reburning zone, and a fuel-lean burnout zone (Figure 3-1). NO_x is destroyed by hydrocarbon radical reactions to form intermediate fixed nitrogen species and, eventually, molecular nitrogen. An overall reaction pathway has been postulated by Chen et al.[8]

As many as 30 years ago, experimental results indicated that NO could be destroyed by reaction with hydrocarbon radicals. This reaction mechanism was commercially utilized in the late 1960's by the John Zink Corporation, which patented a NO_x control process for nitric acid plants based on staged injection of natural gas.[9] Early fundamental studies of NO_x destruction by injection of secondary fuel into the flame zone were performed by Wendt et al, who coined the name "reburning" to describe the process.[10] Concerted effort to develop reburning for application to boilers occurred in Japan during the late 1970's and early 1980's. The first reporting of these efforts was by Takahashi et al, documenting extensive laboratory-, pilot-, and full-scale evaluations of a fuel staging process they refer to as Mitsubishi Advanced Control Technology, or MACT.[11] MACT results indicated that NO_x emissions can be reduced by at least 50 percent, independent of initial NO_x level and fuel type. These promising results have

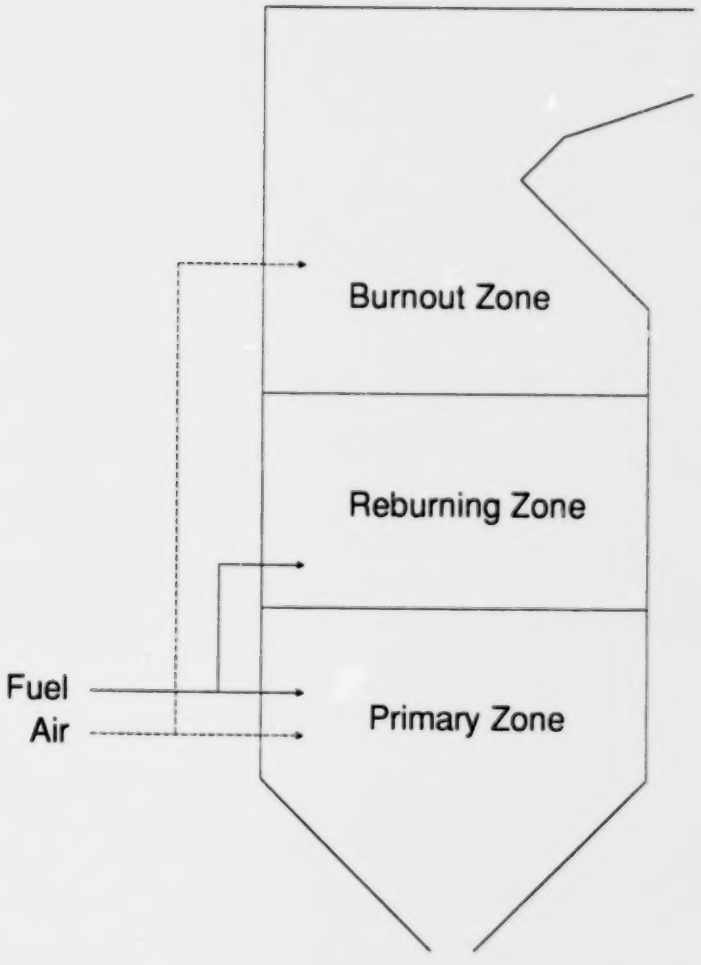


Figure 3-1. The reburning process.

renewed interest in reburning, and further development is being sponsored by the U.S. Environmental Protection Agency (EPA), the Electric Power Research Institute (EPRI), the Gas Research Institute (GRI), and the U.S. Department of Energy (DOE).

Since 1982 EPA has carried out both in-house and extramural bench- and pilot-scale reburning tests. In-house experiments focussed on natural gas and fuel oil reburning.[12-15] Coal reburning tests have been performed for EPA by Energy and Environmental Research Corporation,[8,16] and Acurex Corporation.[17] Significant findings include the dependence of reburning effectiveness on primary flame NO level, reburn zone stoichiometry, and reburn fuel nitrogen content. Fifty percent NO reduction is possible with 10-20 percent of the fuel used for reburning. At low primary NO levels, however, a nitrogen-free reburning fuel (such as natural gas) must be used to achieve 50 percent reduction. Tests show that reburning is effective over a wide range of temperatures and with relatively short reburning zone residence times (less than 0.2 s).

EPA cosponsored with GRI and EPRI a reburning application test on an industrial or small utility coal-fired boiler, beginning in late 1986 and lasting 3-4 years. A field application test of the precombustion chamber burner has also been initiated. Thus, independently, these technologies are nearing the final stage of development.

3.2 EXPERIMENT

The goals of this phase of the study were to develop a multistaged burner design concept that utilizes a half-sized precombustion chamber burner and natural gas reburning to maintain NO_x emissions of less than 175 ppm for primary fuels with up to 5 percent fuel nitrogen dopant. The design minimized boiler modification to maximize retrofit potential and commercial applicability.

3.3 APPARATUS AND METHODS

The primary experimental equipment consisted of the pilot-scale package boiler simulator and precombustion chamber burner (described in Section 2). This facility was fired on natural gas for these tests. Primary fuel nitrogen was simulated by doping ammonia (NH_3) into natural gas.

Secondary natural gas was injected through a water-cooled boom at three axial locations: 107, 30, and 5 cm from the boiler front face. The reburning fuel was injected uniformly into the primary

combustion gas stream during reburning characterization tests, using a spoked injector configuration.[15] Reburning natural gas was injected from a point source at the boiler centerline for the optimization tests described here. Burnout air was injected through eight radial ports in a water-cooled boom, inserted down the boiler centerline through a rear flange, or through axial ports located on the boiler front face. When injected through the centerline boom, the location of the burnout air injection was nominally fixed at the 162 cm axial location.

The experimental facility was designed for independent control and measurement of each fuel, fuel dopant, air stream, stack and in-flame combustion gas speciation, and temperature. Temperature was measured using suction pyrometry. The facility shown schematically in Figure 3-2 is described in Section 2.

3.4 APPROACH

To evaluate this multistaged process for low NO_x, high efficiency combustion, a three part experimental program was devised. First, baseline tests (i.e., no reburning) were performed to evaluate shortened burner (one-module) performance. First-stage stoichiometry and simulated primary fuel nitrogen content were varied. Results were compared with long burner (two-module) results. Second, parametric tests were performed to evaluate reburning effectiveness under ideal mixing conditions as a function of primary zone NO (NO_{pri}) level, reburn zone stoichiometry (SR_R), and simulated reburn fuel nitrogen content. These results have been previously reported and are summarized here.[12-15] Third, preliminary tests were performed with the shortened prechamber burner for optimum reburning application. These results are discussed and current tests on a new test burner are described.

3.5 BASELINE TEST RESULTS

At a primary burner firing rate of 0.6 MW and a nominal first-stage stoichiometry of 0.7, shortening the precombustion chamber burner length by removing one of the two modules decreased the bulk combustion gas first-stage residence time from 600 to 350 ms. In baseline tests (without reburning), first-stage stoichiometry was varied, with exhaust excess air held constant at about 15 percent. Ammonia was doped into the natural gas fuel stream, resulting in a fuel nitrogen content of 0.66 percent. In Figure 3-3 data are shown for both the short and long burner configurations. The minimum NO emission

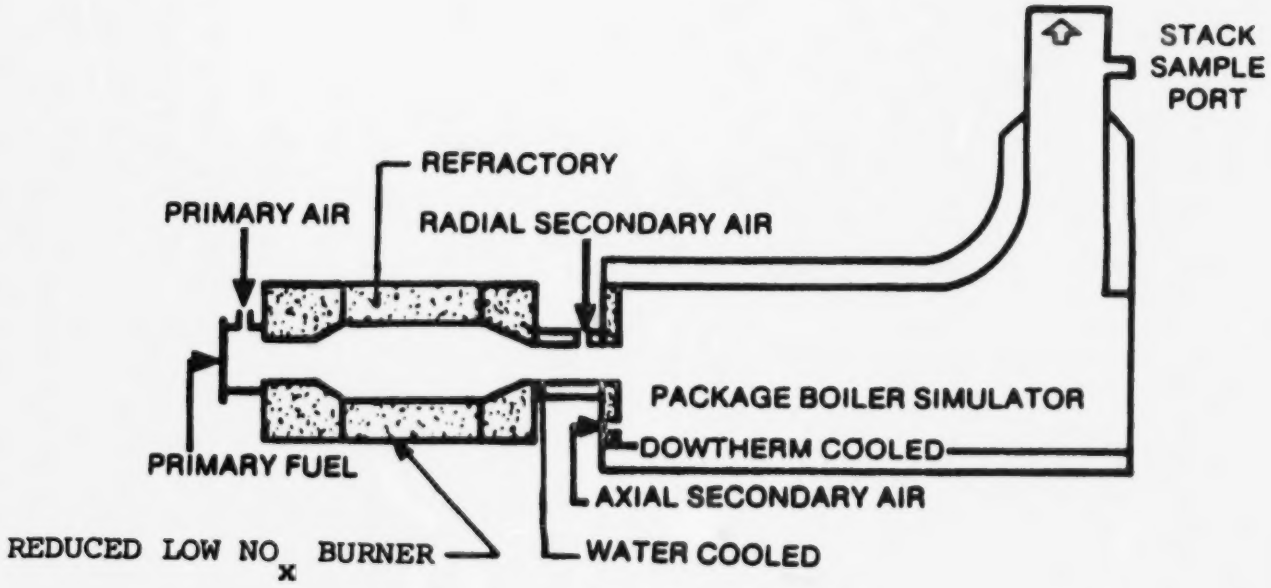


Figure 3-2. Pilot-scale research facility.

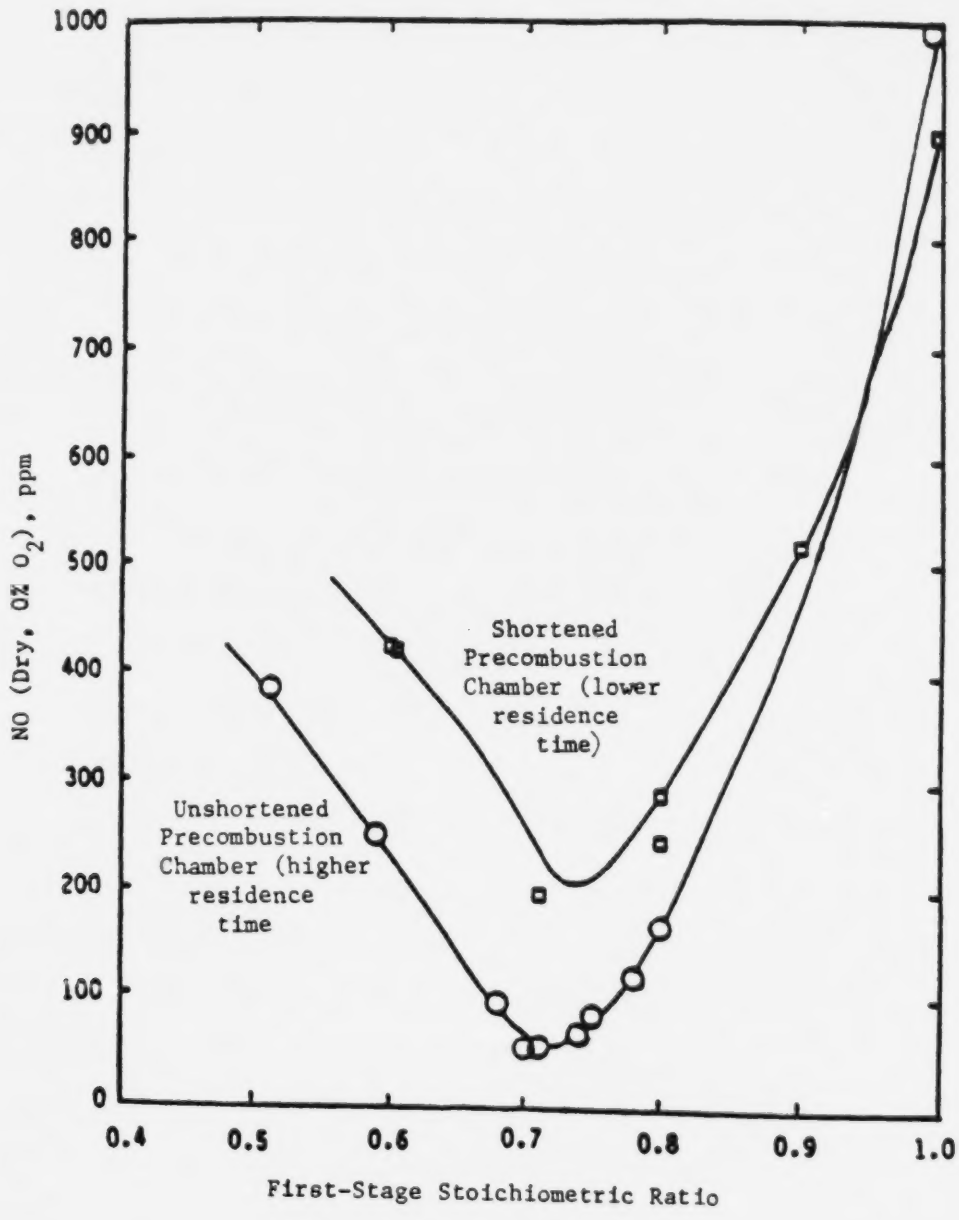


Figure 3-3. Influence of first-stage residence time on NO emission for short and long preburner configurations.

was observed at a first-stage stoichiometry of about 0.7, consistent with England's data at a similar scale test.[7] The sharp minimum in the curve indicated the sensitivity of NO emission to first-stage stoichiometry. The minimum NO emission increased from 50-75 to 200-250 ppm in going to the shortened burner. These ranges represented average NO emissions achievable given the small fluctuations in fuel and air flows.

The amount of NH_3 dopant was varied at the optimum first-stage stoichiometry (0.7) for both the short and long burner configuration. The data in Figure 3-4 show that NO levels in the short burner are more sensitive to fuel nitrogen content than the long burner. With no NH_3 addition, NO emission from the short burner was 90 ppm; from the long burner the NO emission was 40 ppm. These levels indicated the thermal NO component of the NO emission, coming from the molecular nitrogen (N_2) in the air. During operation with the short burner, a longer flame was observed in the boiler than during operation with the long burner. This is because combustion of the hydrocarbon was less advanced at the secondary air addition location for the short burner. Consequently, the peak temperatures in the boiler burnout zone were slightly higher than for the long burner. With the addition of NH_3 dopant the long burner NO emissions increased to 100 ppm, or a net 60 ppm contribution from the surrogate fuel nitrogen. The short burner NO emissions for high NH_3 dopant levels in the fuel stream approached 250 ppm, or a 160 ppm net increase due to fuel nitrogen. The reduced first-stage residence time resulted in less fuel nitrogen being reduced to N_2 in the fuel-rich precombustion chamber. As fuel nitrogen content increased above 2 percent the resulting increase in NO emissions became small.

Thus, an effect of halving the burner size is to increase minimum NO emissions for high nitrogen fuels from 100-250 ppm. Another effect is to move some of the flame back into the boiler, although still much of the heat release remains in the preburner. With a shorter flame length in the boiler with the preburner than with conventional burner, reburning, which requires boiler volume, is an ideal technology for achieving additional in-furnace NO reduction. Before discussing preliminary tests combining the reburning and precombustion chamber burner technologies, reburning characterization tests are discussed.

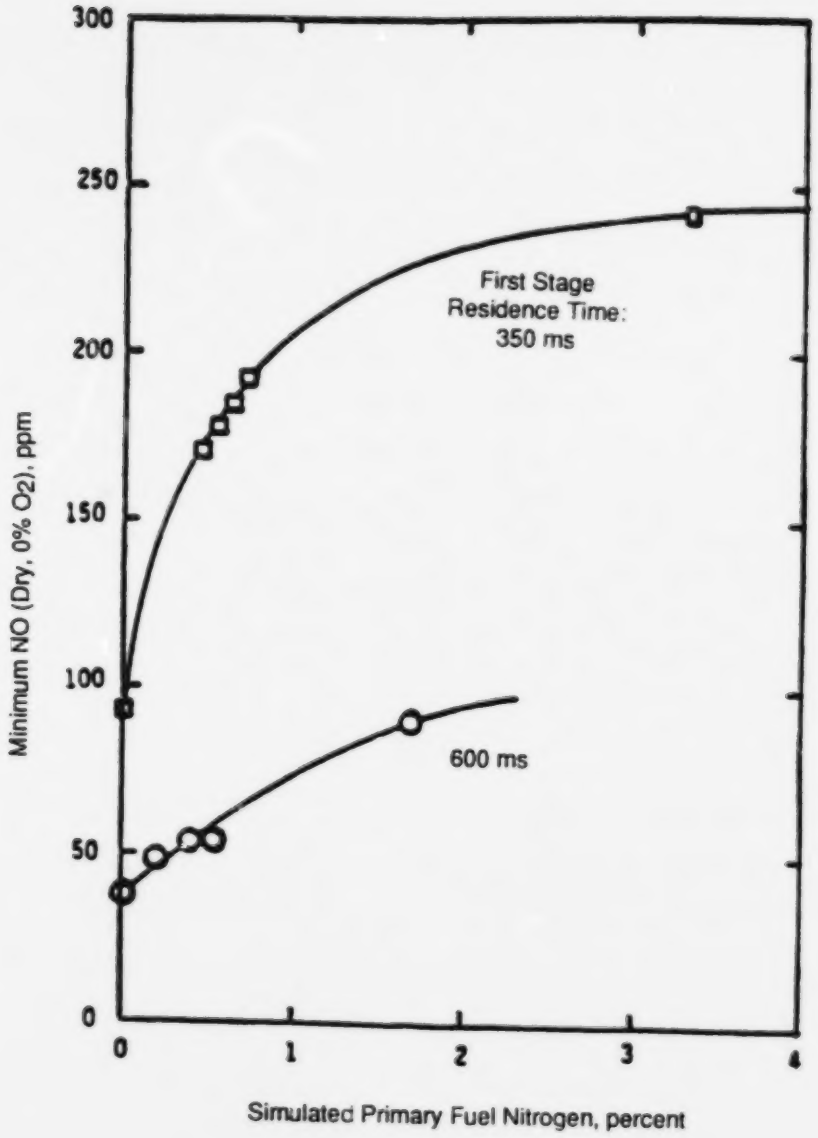


Figure 3-4. Influence of fuel nitrogen content on minimum NO emission for short and long preburner configurations.

3.6 REBURNING CHARACTERIZATION TEST RESULTS

Reburning involves staging a portion of the fuel and air streams downstream of the primary flame to reduce NO in the primary combustion gases. Parametric tests were performed previously in the package boiler simulator in which primary NO was varied between 50-500 ppm and reburn zone stoichiometry was varied from 1.0-0.75.[15] In these tests primary load was held constant at 0.6 MW, first-stage stoichiometry was fixed at 0.6 (off-optimum), and primary and burnout zone stoichiometries were held constant at 1.1. The secondary natural gas was injected at a 1.02 m axial location, just downstream of the visible primary flame. Using a spoked fuel injector, natural gas was injected to match the flux of free oxygen from the primary zone, thereby providing radial uniformity in the reburn zone stoichiometry. Burnout air was added at the 1.62 m axial location. Primary NO was varied by varying the primary fuel NH_3 dopant level. Reburn zone stoichiometry was varied by varying the reburn fuel and air flowrates. This procedure provided sufficient control to measure the maximum reburning effectiveness in the package boiler simulator.

Results from these natural gas reburning tests are summarized in Figure 3-5. The strong dependence of NO reduction to primary NO is in agreement with the results reported by Chen[8] but in conflict with the MACT claim.[11] Analysis of the data in Figure 3-5 suggests that the overall NO destruction rate has a partial order with respect to primary NO of 1.5-1.6. That is,

$$d[NO]/dt = C\,[NO_{pri}]^{1.5\text{-}1.6}$$

Additional data were taken to evaluate reburning fuel nitrogen effects.[13] From this data a contour map was drawn depicting the relationship between overall NO reduction by reburning and two controlling parameters: reburning fuel nitrogen content and primary NO level. In Figure 3-6 it is shown that 50 percent NO reduction is not possible for primary NO levels less than 140 ppm. For NO levels less than 250 ppm, fuel nitrogen content limits NO reduction. For example, at an initial NO level of 200 ppm, reburning with fuels exceeding 1 percent in fuel nitrogen results in increased NO emissions.

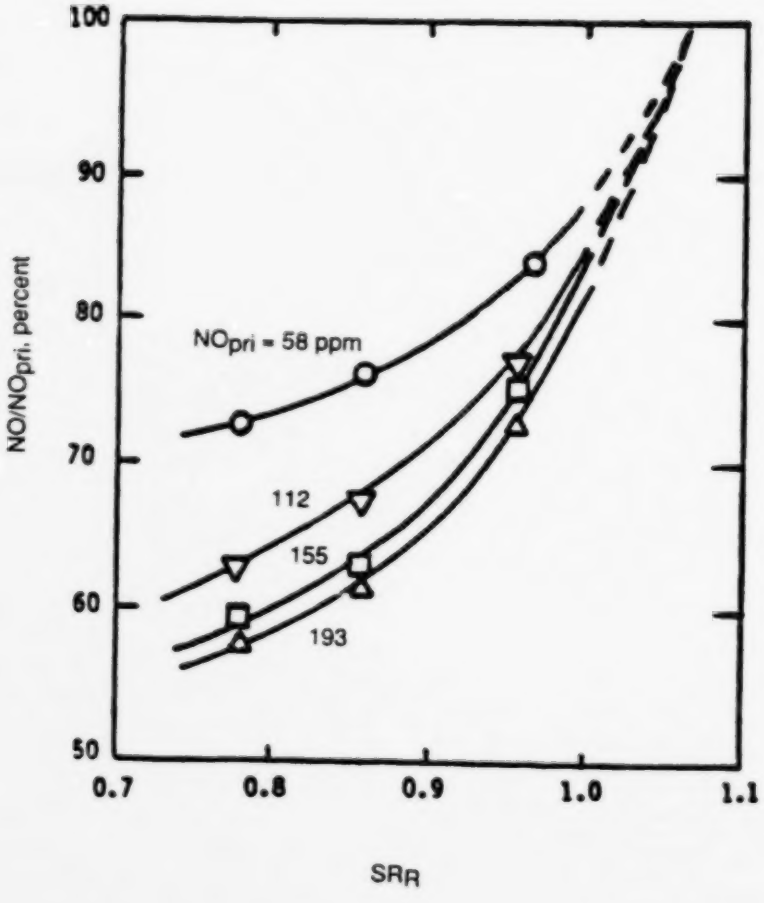


Figure 3-5. NO reduction for natural gas reburning application.

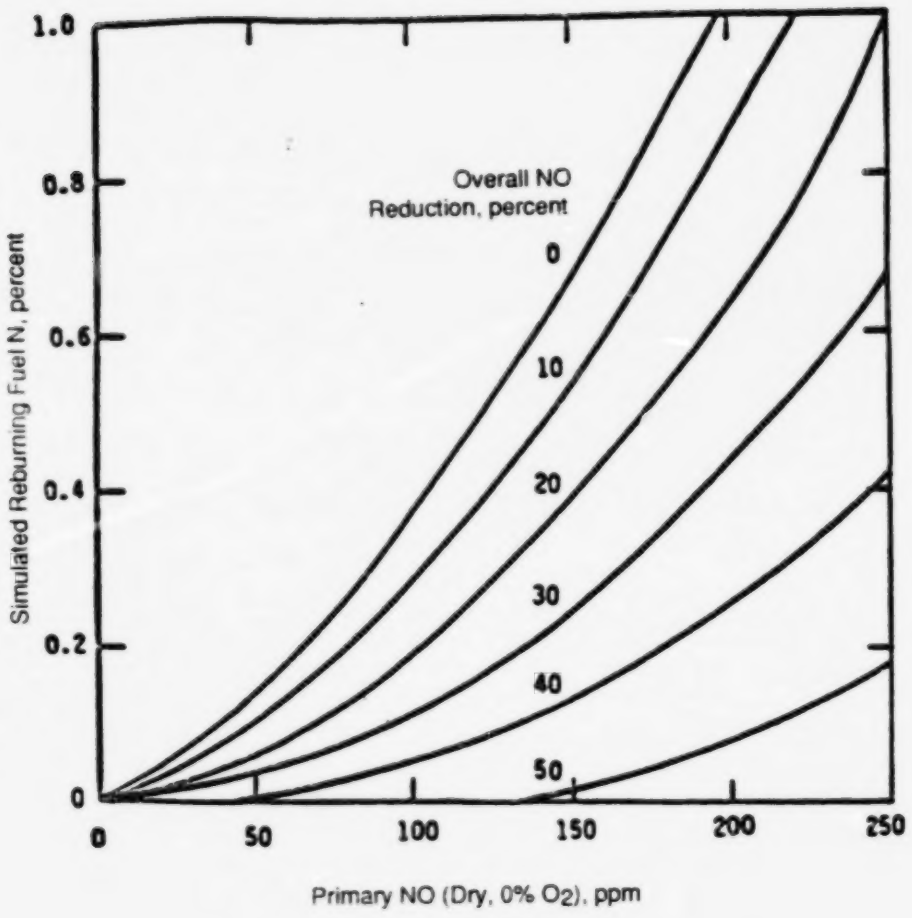


Figure 3-6. Contour map of optimum NO reduction by reburning. From Ref. 5.

Based on these results from reburning tests performed under idealized mixing conditions, it was hypothesized that reburning applied in tandem with the precombustion chamber burner could produce NO emissions of less than 175 ppm for gaseous and liquid primary fuels with up to 5 percent fuel nitrogen.

3.7 PRELIMINARY PROOF-OF-CONCEPT TEST RESULTS

Preliminary tests were performed to evaluate the concept of natural gas reburning of combustion gases from a half-sized precombustion chamber burner. A primary NO level of 260 ppm was maintained by operating the burner at an off-optimum stoichiometry of 0.65 to reduce the amount of fixed nitrogen dopant (NH_3) required to achieve this emission. This NO level represents the maximum emission of the half-sized burner when burning fuels with up to a 4 percent fuel nitrogen. Primary flame zone stoichiometry leaving the preburner was fixed at 1.1. The locations of staged fuel and air addition were varied.

Figure 3-7 shows the effect of reburn fuel injection location on NO emissions. Reburning fuel was added at the 107, 30, and 10 cm axial locations in the boiler. Burnout air was added at 168 cm. From Figure 3-7 it is observed that slightly lower NO emissions were achieved on injecting the reburn fuel downstream of the primary flame. However, even injecting reburn fuel at the outlet of the precombustion chamber resulted in significantly reduced NO emissions. The data suggest that reburn fuel can be injected at the boiler front face and still achieve NO emissions of less than 175 ppm.

Figure 3-8 shows the effect of burnout air injection location on exhaust NO levels. With reburning fuel injected at 30 cm, air was injected through axial ports on the boiler front face. The results show only slightly higher NO emissions than with deep-staged (168 cm) burnout air. Thus, injecting burnout air from the boiler front face results in NO emissions that approach the 175 ppm level.

3.8 DISCUSSION AND CONCLUSIONS

Based on the data presented in Figures 3-4 and 3-6, predictions can be made of NO emissions as a function of primary and secondary fuel nitrogen content. However, by injecting fuel and air on the front face of the boiler a reduction in reburning effectiveness was observed (Figures 3-7 and 3-8). With 250 ppm primary NO, a 42 percent reduction was achievable for reburning with a nitrogen-free fuel at the boiler front face versus 55 percent reburning downstream of the primary flame with uniform injection

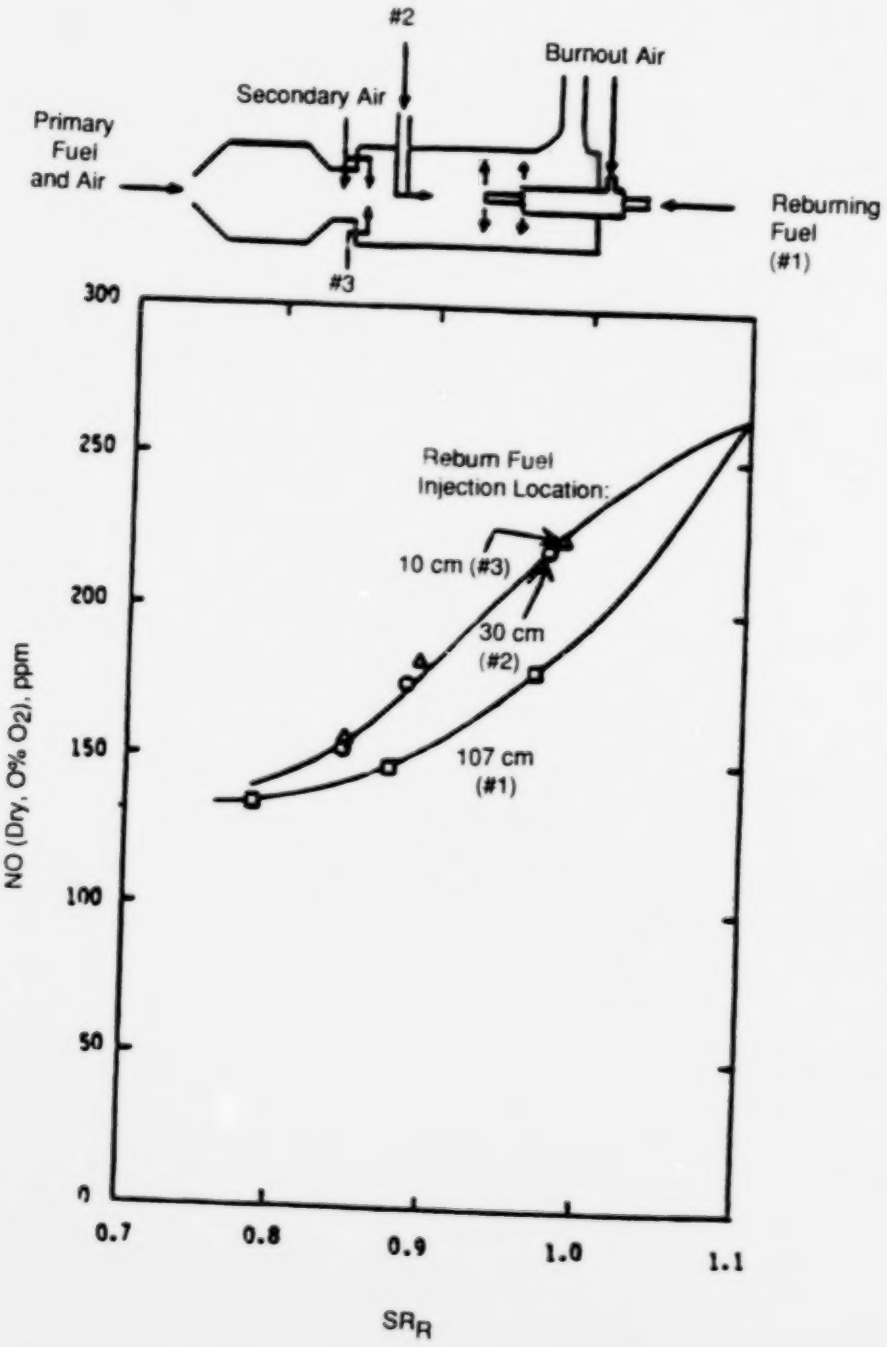


Figure 3-7. NO emissions as a function of reburn zone stiochiometry for various reburn fuel injection locations.

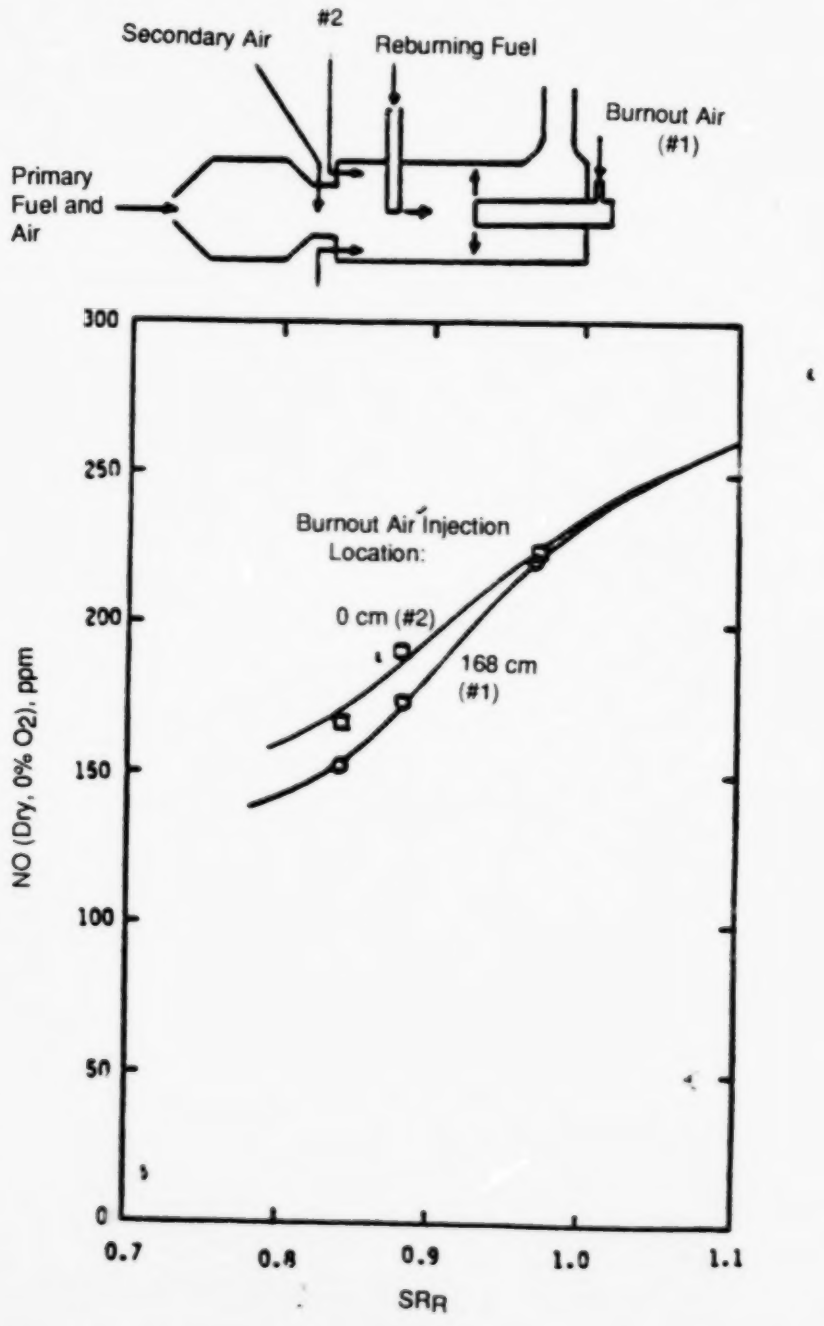


Figure 3-8. NO emissions as a function of reburn zone stoichiometry for various burnout air injection locations.

(Figure 3-6). Though insufficient data are available to make a new contour map of reburning effectiveness versus primary NO for reburning application from the boiler front face, it can be conservatively assumed here that reburning effectiveness is reduced by 10-15 percent from downstream uniform reburning application. Carbon monoxide (CO) emissions for all the tests performed were lower than 35 ppm, indicating that combustion efficiencies attained were greater than 99 percent.

SECTION 4

NEW BURNER TESTS

4.1 INTRODUCTION

Proof-of-Concept tests, explained in Section 2, showed that a low NO_x strategy using a precombustion chamber burner and reburning (from the front end of the boiler) was attractive from the standpoint of NO_x reduction and high combustion efficiency. Based on the results of these tests, a new burner system was designed and installed by Acurex. To increase the burner temperatures by reducing the radiative heat loss to the boiler and to take advantage of thermal buoyancy effects, the burner was made vertical. This design also contained four removeable, small modules that vary burner length over a wide range, allowing residence time studies. The new burner is shown in Figure 2-4.

4.2 EXPERIMENTAL METHODS

The goal of this study was to minimize NO_x formation, with an emission target of 175 ppm (dry, at zero percent O_2) or less, and maintain efficient incineration of surrogate fuel/waste mixtures with up to 5 percent fuel nitrogen by using a precombustion chamber burner reduced in size by about half.

The facility shown schematically in Figure 4-1 was described in Section 2. For these tests a burner length of 1.8 m was used, corresponding to a nominal residence time of 250 ms. A 5 cm diameter port was available for staging fuel into the burner. Two of the eight axial air ports on the package boiler simulator front face were modified to provide ports for staging fuel into the boiler at an angle of 45°. This design allowed reburning application from the front face of the boiler. The end plate of the boiler was modified to allow the insertion of a water-cooled boom injector for deep staging of air into the boiler.

As explained in Section 2, the experimental facility was designed for independent control and measurement of each fuel, fuel dopant, and air stream. Stack gas speciation was measured by a continuous emissions monitoring system. NO and NO_x were measured by chemiluminescence. Reported in this section are NO measurements only, measured on a dry basis and corrected to 0 percent

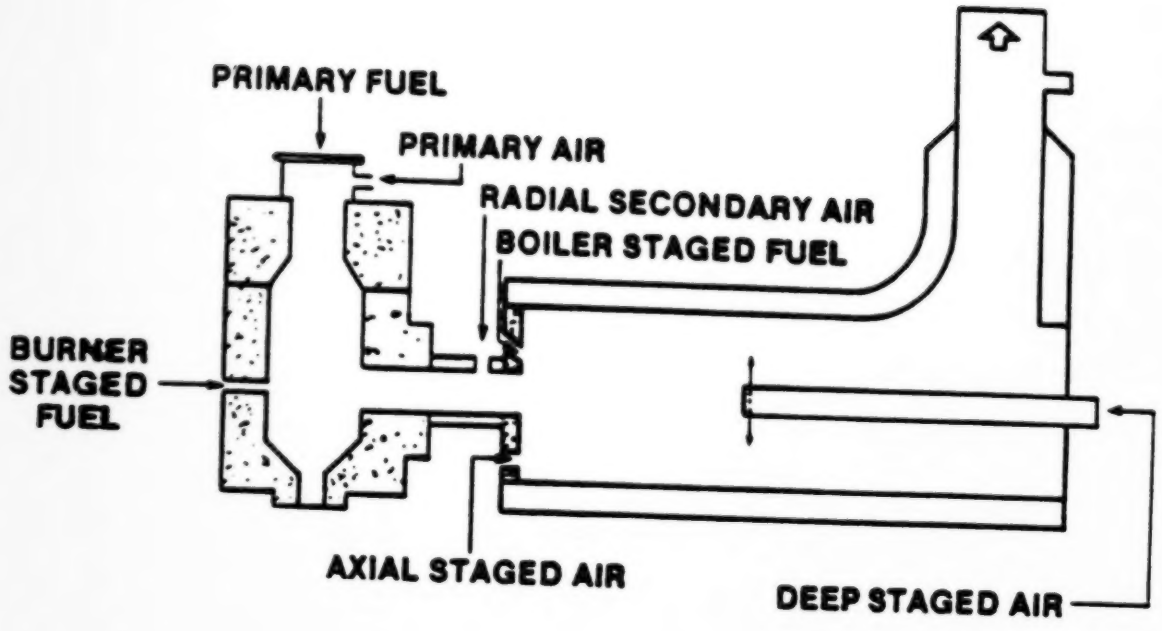


Figure 4-1. Pilot scale combustion research facility. The package boiler simulator has been fitted with a precombustion chamber burner and air and fuel staging ports.

O_2. Spot-check measurements of NO_x indicated that NO emissions accounted for over 95 percent of the exhaust NO_x emissions in these tests.

A 0.7 MW North American (NA) Scotch-type package boiler was used to provide conventional burner results for comparison with the multistaged burner results. This boiler is a three-pass unit, with a continuous service rating of 0.3 kg of steam per second (2,400 lb/h). Its size and thermal characteristics are nearly identical to those of the package boiler simulator.[12,14]

Evaluated were burner baseline performance and burner operation with various air staged and fuel staged NO_x controls. The parameters affecting the NO_x emissions from the facility with unstaged controls were fuel nitrogen content, combustion gas residence time in the prechamber, first-stage stoichiometry, and exhaust stoichiometry. The residence time of combustion gas in the burner depended on precombustion chamber length, load, and stoichiometry. The nominal load was 0.6 MW. The exhaust stoichiometry was kept at a nominal value of 15 percent excess air, as per commercial boiler practice. Nominal fuel nitrogen content for the fuel oil/pyridine mixture was 2 percent by weight; for the natural gas/ammonia fuel the nominal fuel nitrogen content was 5.8 percent. First-stage stoichiometry was optimized for each NO_x control application tested.

4.3 BURNER BASELINE PERFORMANCE

During low NO_x burner characterization tests, the effects of first-stage stoichiometry, excess air, load, and fuel nitrogen content on NO emissions were studied.

First-stage stoichiometry was varied by changing the primary air flow. Secondary radial air was adjusted to maintain 15 percent excess air. The results are plotted in Figure 4-2. The curves indicate a strong sensitivity of stack NO to changes in burner stoichiometry. At nominal fuel nitrogen, for the gas tests, a minimum NO emission of 315 ppm occurred at a burner stoichiometry of about 0.78; for the oil tests, a minimum of 190 ppm occurred at 0.65. Thus, additional combustion modifications were necessary to meet the program goal of less than 175 ppm.

Additional tests were done with gas/ammonia mixtures with 2 percent fuel nitrogen content. The results are also plotted in Figure 4-2. The shift in optimum burner stoichiometry suggests a variation in the thermal environment in the precombustion chamber. In Figure 4-3 burner temperatures are shown,

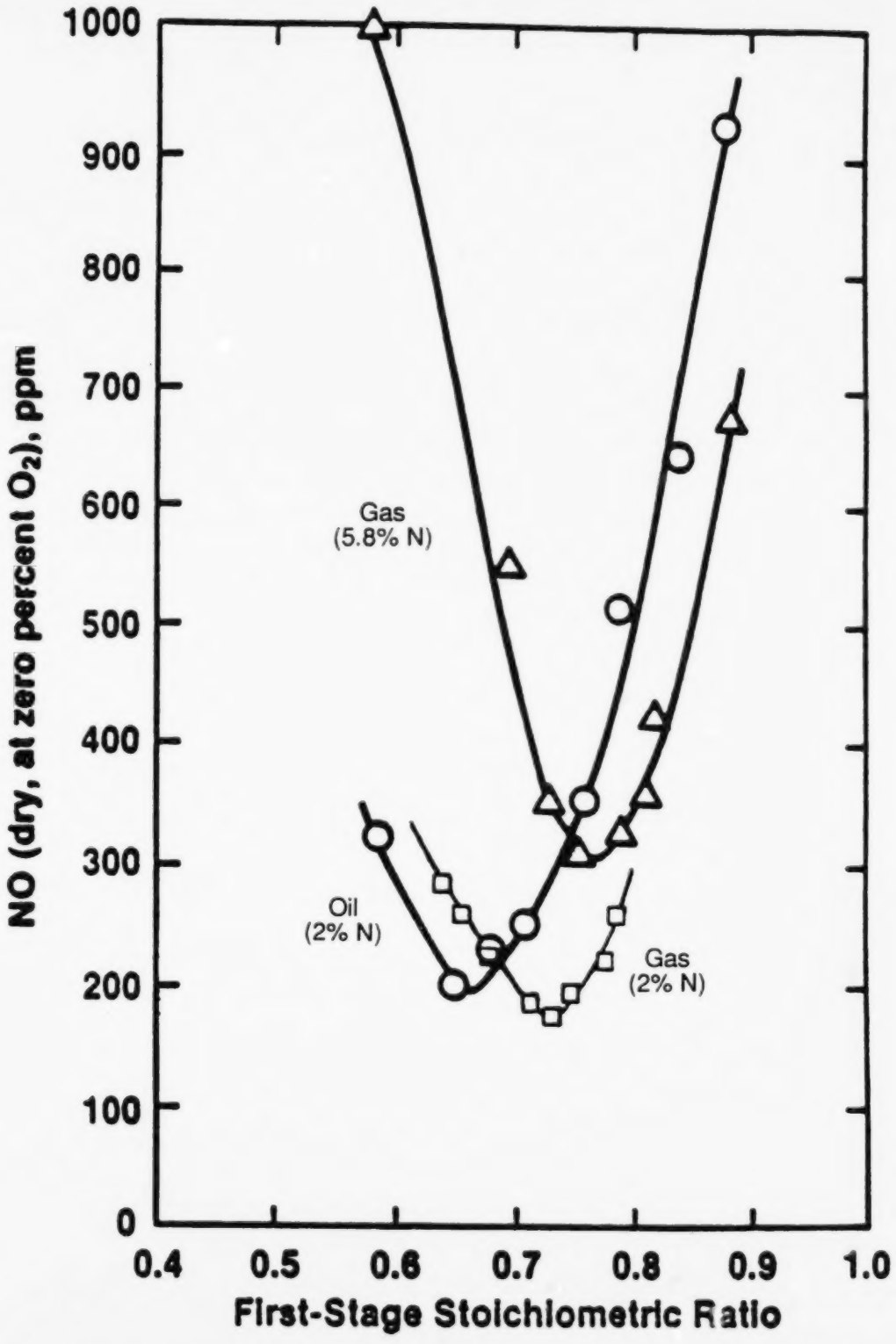


Figure 4-2. Effect of burner stoichiometry. Shown are results from tests firing 2.0 percent and 5.8 percent nitrogen gas fuel and a 2.0 percent nitrogen distillate fuel oil/pyridine mixture.

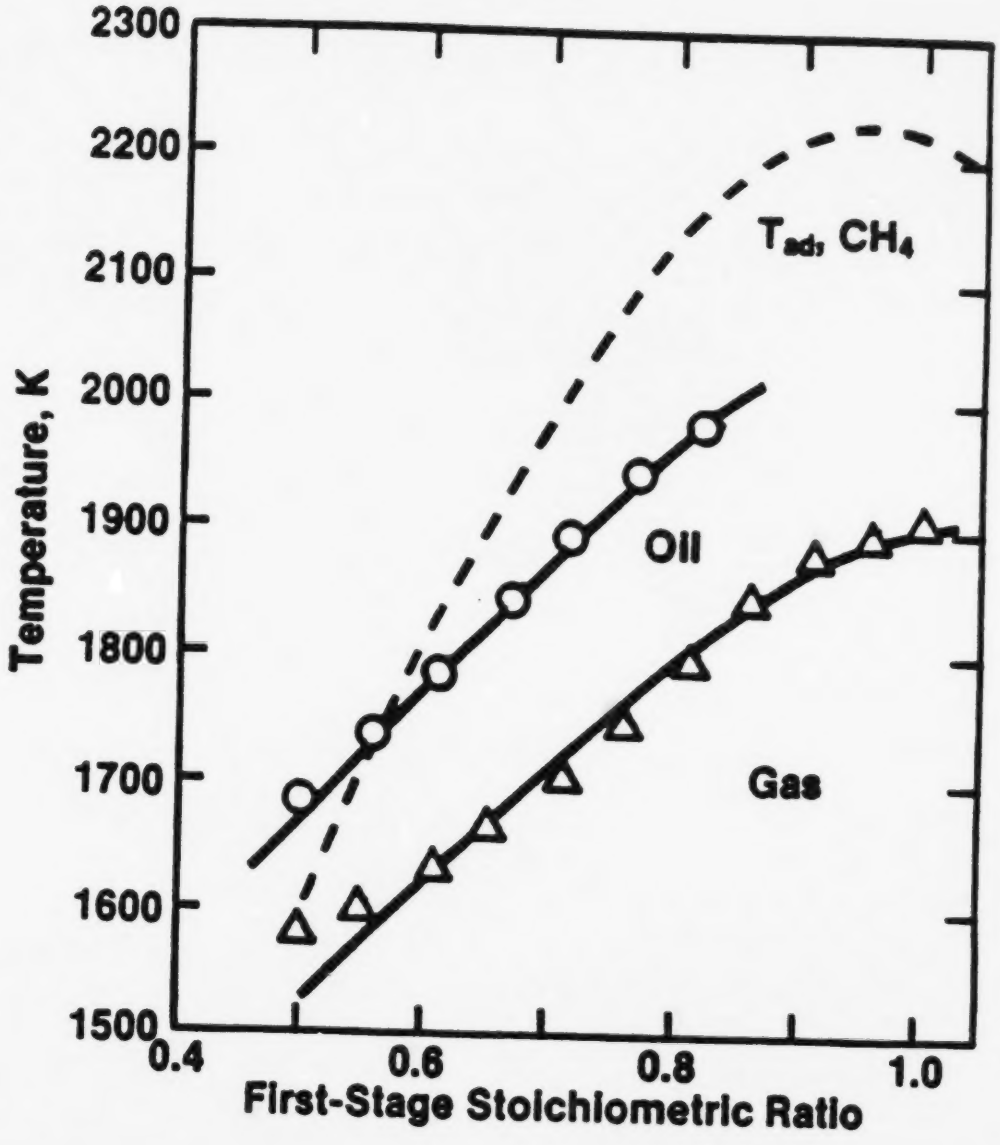


Figure 4-3. Burner temperatures. Shown are measurements firing the low NO_x burner on gas and oil fuels. The dashed line represents the adiabatic flame temperature of methane in air at 1 atm.

measured by suction pyrometry. Radiation and conduction errors are estimated to be less than 30 °C. The burner temperatures were found to be higher for the oil tests; thus, the shift in optimum stoichiometry.6

In tests on the North American boiler, a NO emission of 1,000 ppm resulted when firing the 5.8 percent nitrogen gas fuel at 15 percent excess air. A NO emission of 765 ppm resulted when firing the 2 percent nitrogen oil mixture at 15 percent excess air. Thus, the low NO_x burner reduced NO emissions by 68 percent for the gas fuel and by 75 percent for the oil mixture.

4.3.1 Excess Air Variation

The effect of excess air variation on stack NO is shown in Figure 4-4. Excess air had a much stronger effect in the conventional North American burner tests than in the low NO_x burner tests, as expected. While reducing excess air provided some NO reduction with the low NO_x burner, maintaining an exhaust excess air level of 15 percent was important for achieving high combustion efficiency.

4.3.2 Load Variation

The effect of load reduction on stack NO is shown in Figure 4-5. As load was decreased from a nominal condition of 0.6 MW to 65 percent of nominal, the stack NO concentration dropped by 20-25 percent in the low NO_x burner tests. With a conventional burner, NO emissions are reduced only slightly with burner derating, due to decreased air/fuel mixing intensity. However, with the low NO_x burner, the effect is much greater because load reduction corresponds to an increase in first-stage residence time and, thus, a decrease in NO emission. Reducing load by 35 percent increased burner residence time from 250-385 ms. However, boiler steam requirements make load reduction an impractical means of NO_x control.

4.3.3 Fuel Nitrogen Variation

The effect of fuel nitrogen variation is shown in Figure 4-6. Exhaust NO level increased with increasing fuel nitrogen content in the fuel/waste stream, as expected, with a much greater sensitivity observed in the conventional North American burner tests. These results demonstrate the precombustion chamber burner's ability to reduce fuel nitrogen to molecular nitrogen, even with its reduced size

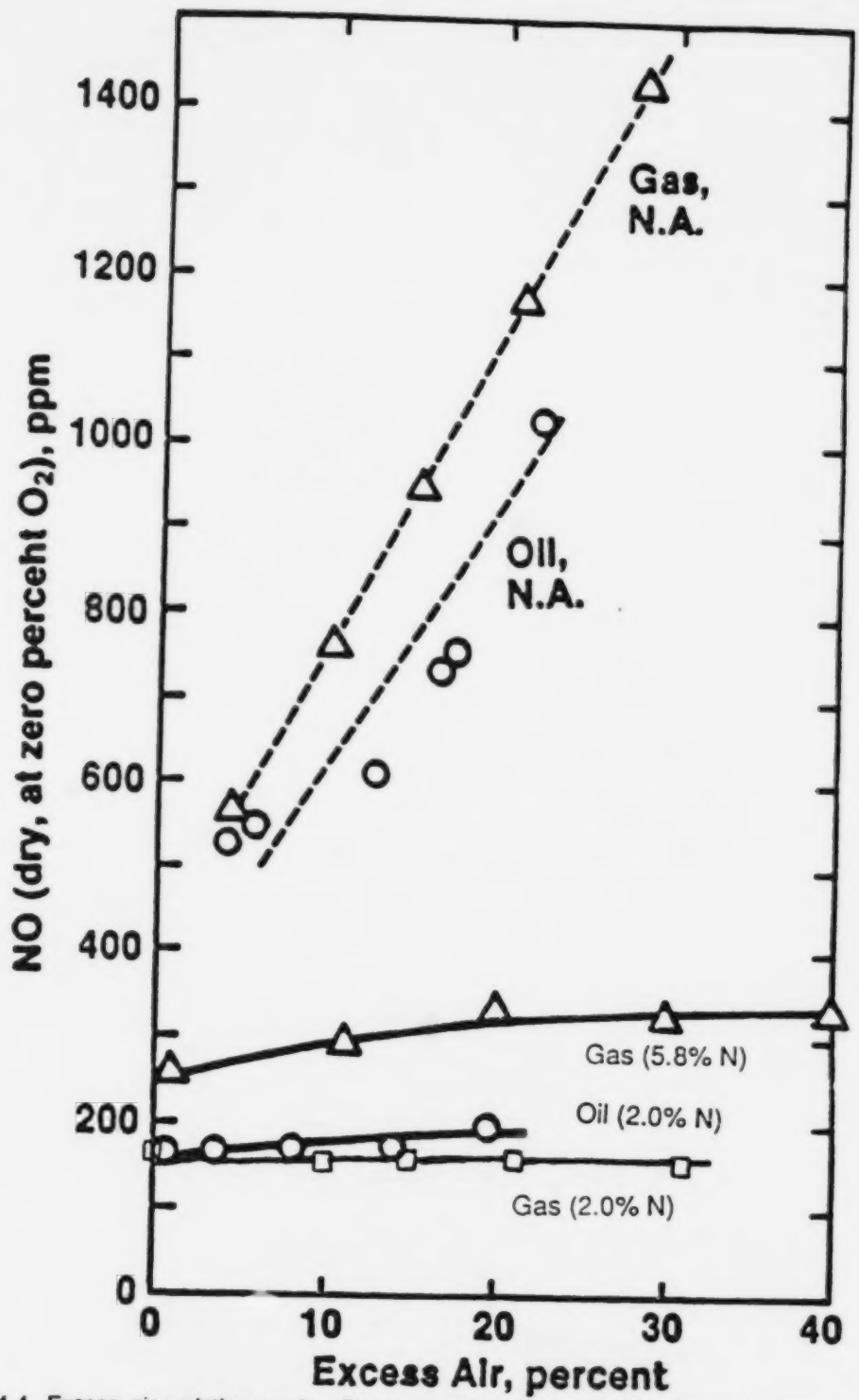


Figure 4-4. Excess air variation results. Shown are 2.0 percent and 5.8 percent nitrogen oil results. The dashed lines represent results from the North American (N.A.) boiler tests.

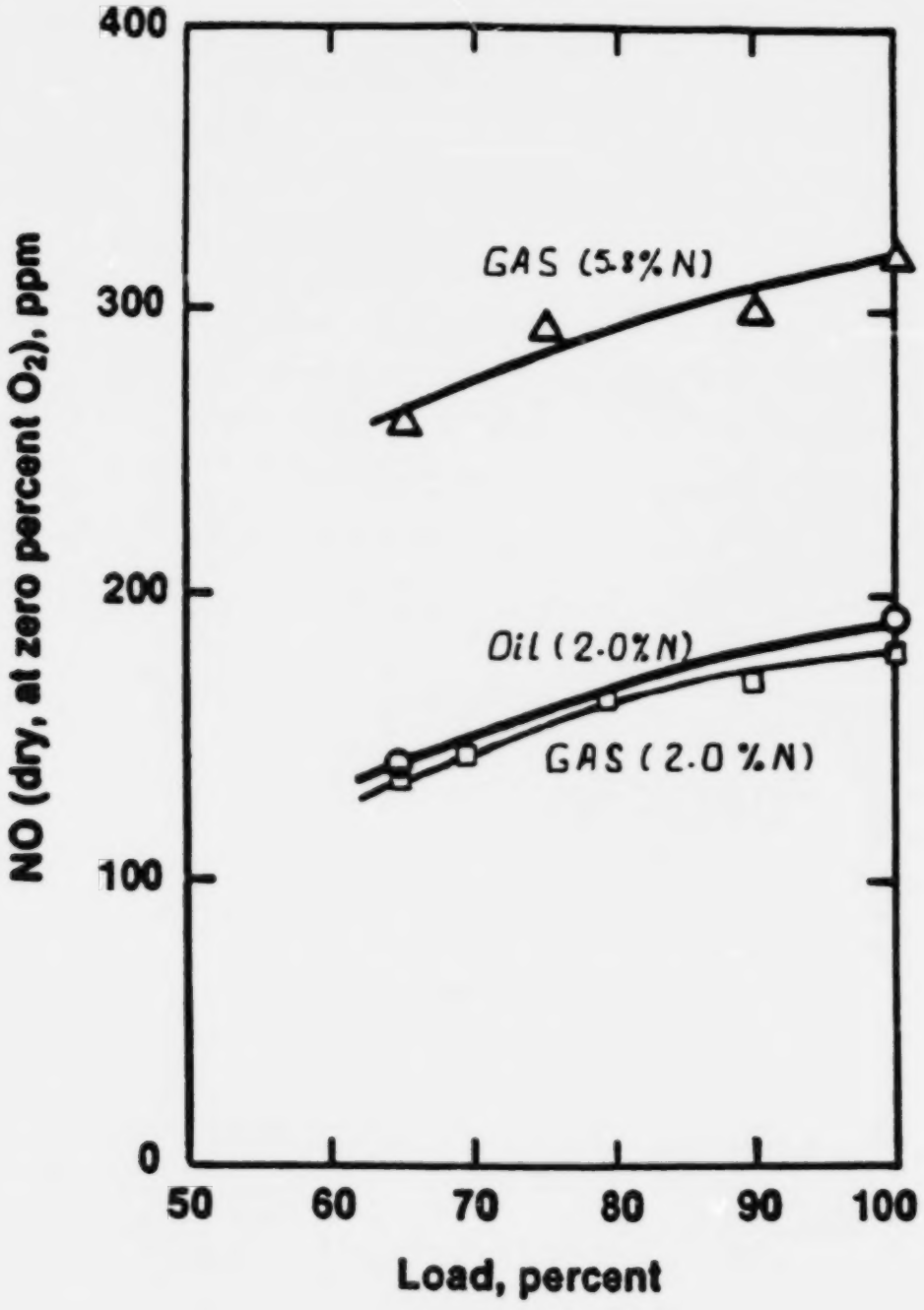


Figure 4-5. Load variation results. Shown are results with 2.0 percent and 5.8 percent nitrogen gas fuel and a 2.0 percent nitrogen oil mixture.

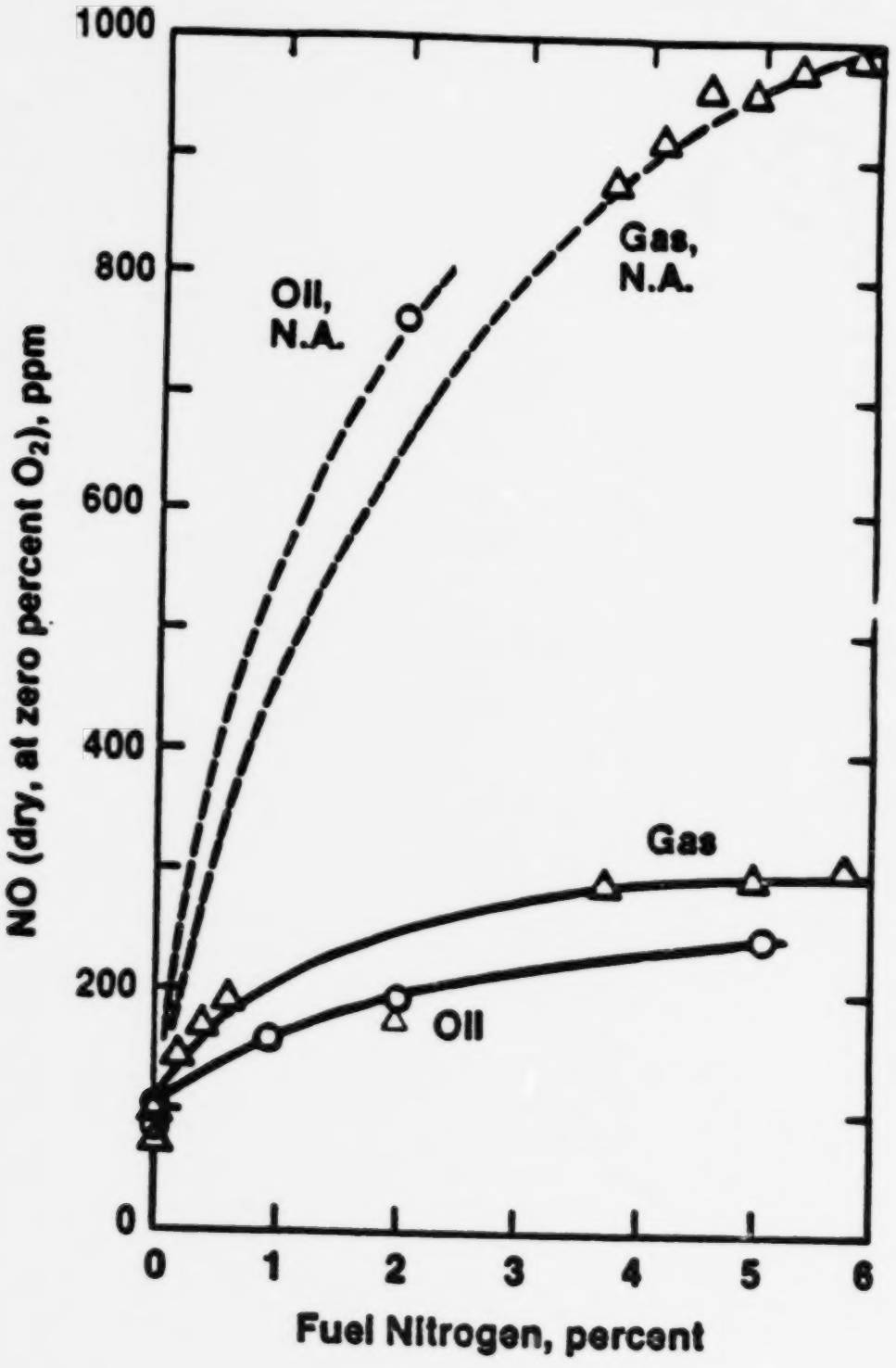


Figure 4-6. Fuel nitrogen variation results. The dashed lines represent data from the North American (N.A.) boiler tests.

(250 ms). The full size (600-800 ms) precombustion chamber burner produces NO emissions even less sensitive to fuel nitrogen content.6

4.4 AIR STAGED NO_x CONTROLS

During air staged NO_x control tests, the effect of moving the location of secondary air addition from the radial ports in the transition section to the axial and deep staged ports in the boiler was examined. The secondary air was distributed between radial and axial locations in one series of staging tests, and between radial and deep staged ports (located 132 cm from the boiler front face in a second series of tests. This created a three-stage combustion process: a fuel-rich burner zone, a less fuel-rich (SR_2) zone after radial secondary air injection in the transition section, and a fuel-lean burnout zone after final air addition. A water-cooled boom, aligned with the centerline axis of the boiler, supplied the deep staged air.

Fuel oil/pyridine and natural gas/ammonia test results for the two cases of secondary air staging in the boiler are given in Figure 4-7. The axial air staging resulted in a drop in minimum NO concentration from 190 ppm, with no staging, to 150 ppm for the fuel oil/pyridine burning, and from 315 ppm to 220 ppm for the natural gas/ammonia burning with 100 percent of the secondary combustion air moved from the radial injectors to the axial injectors. The reduced NO levels for air staging were caused by lower combustion gas temperatures and delayed mixing of the secondary air and combustion gas. Hence, less thermal NO was generated and less fuel nitrogen species fragments were oxidized with axial air addition into the boiler than with radial air addition into the transition section. Similarly, lower temperatures in the boiler at the deep staged air location and longer fuel-rich zone residence time resulted in a lower NO emission when the secondary air was deep staged. With all of the secondary air added from the deep staged location, the minimum NO level was 130 ppm for the fuel oil/pyridine case and 160 ppm for natural gas/ammonia case.

From the test results just described, deep staging of secondary air is shown to be an effective means of minimizing NO emissions. However, such staging may lead to burnout problems, which are of great concern when cofiring waste. Extending the fuel-rich zone from the precombustion chamber into the boiler exposes the reducing combustion gases to cool boiler walls, which may result in slagging

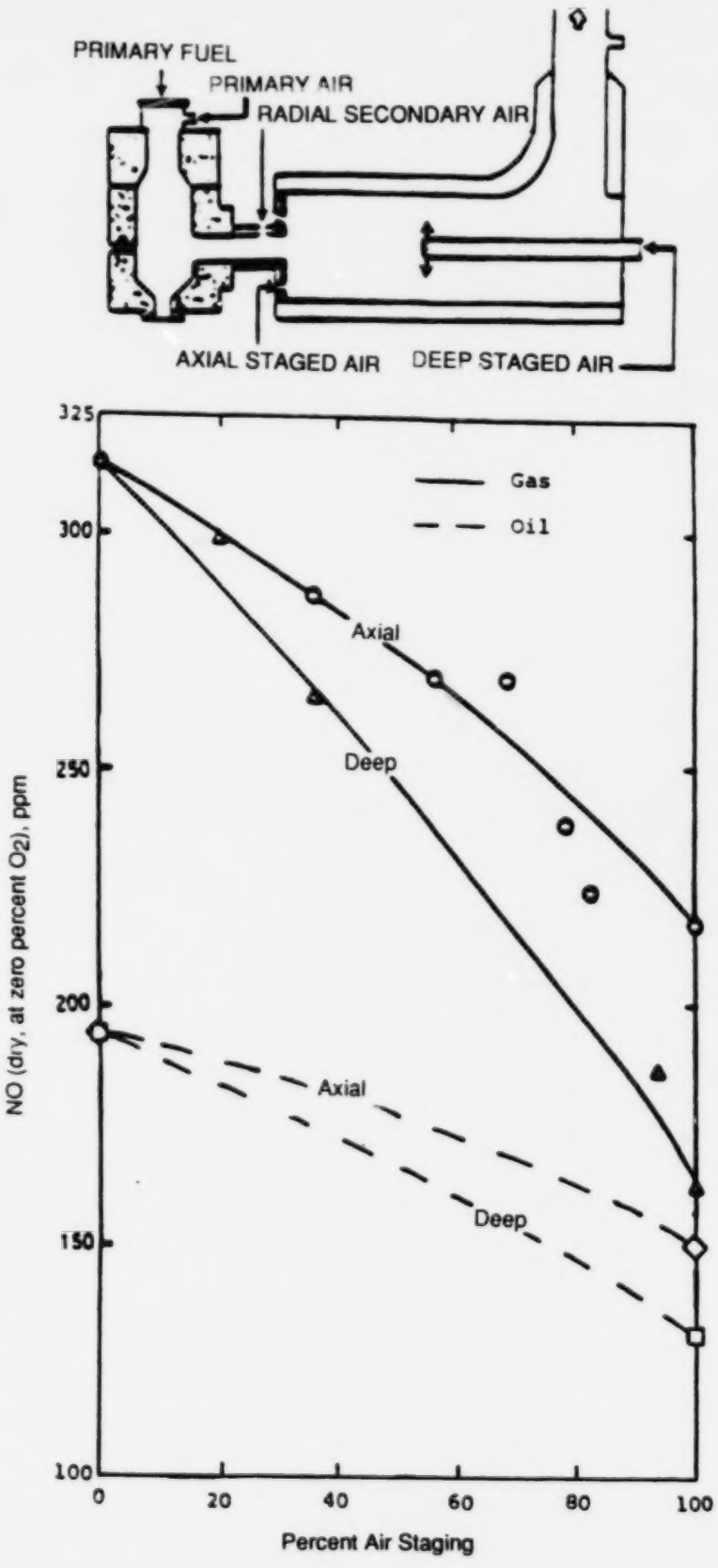


Figure 4-7. Air staging results. Shown are results from firing a 5.8 percent nitrogen gas fuel and a 2.0 percent nitrogen oil mixture.

and/or sooting. Further, the lower combustion gas temperatures in the boiler slow the fuel-rich nitrogen kinetics.

4.5 FUEL STAGED NO_x CONTROLS

During fuel staged NO_x control tests, the effect of diverting part of the primary fuel to staged locations in the burner and boiler was studied. The staged fuel was natural gas, with no ammonia dopant. In the case of fuel staging in the burner, the secondary natural gas was added, using a water-cooled injector, down the centerline axis of the boiler; secondary air was added axially into the boiler to allow sufficient fuel-rich zone residence time. In the case of fuel staging in the boiler, the secondary natural gas was added at an angle of 45°, using water-cooled injectors, from two ports in the boiler front face. Secondary air to complete primary fuel combustion was added radially into the transition section, while burnout air for secondary fuel combustion was added axially near the boiler wall, using six axial ports on the boiler front face.

4.5.1 Burner Fuel Staging

Holding total load constant, fuel was diverted from the primary fuel injector to a secondary injector near the precombustion chamber exit (see Figure 4-1), thus creating two stoichiometric zones in the burner in addition to the burnout zone in the boiler. The staged fuel was undoped (nitrogen-free) natural gas. Secondary air was injected through the axial injectors. Two effects may contribute to a decrease in NO emissions with this fuel staging scheme: 1) possible acceleration of fuel nitrogen reduction mechanisms due to increased hydrocarbon radical concentrations, and 2) dilution of primary combustion gases by secondary combustion gases.

Fuel oil/pyridine and natural gas/ammonia results are given in Figure 4-8. With optimized burner stoichiometric ratios (0.7 for natural gas/ammonia and 0.65 for distillate fuel oil/pyridine) and 35 percent fuel staging, the decreases in NO levels were from 220 ppm to 190 ppm and from 150 ppm to 110 ppm for the cases of 5.8 percent fuel nitrogen gas/ammonia and 2.0 percent fuel nitrogen distillate fuel oil/pyridine mixtures. It is interesting to note that with no fuel staging, the NO levels are 220 ppm and 150 ppm for the (5.8 percent N) gas and (2.0 percent N) oil tests respectively with this test configuration where secondary air is injected axially, as opposed to 315 ppm and 190 ppm (Figure 4-5) obtained in

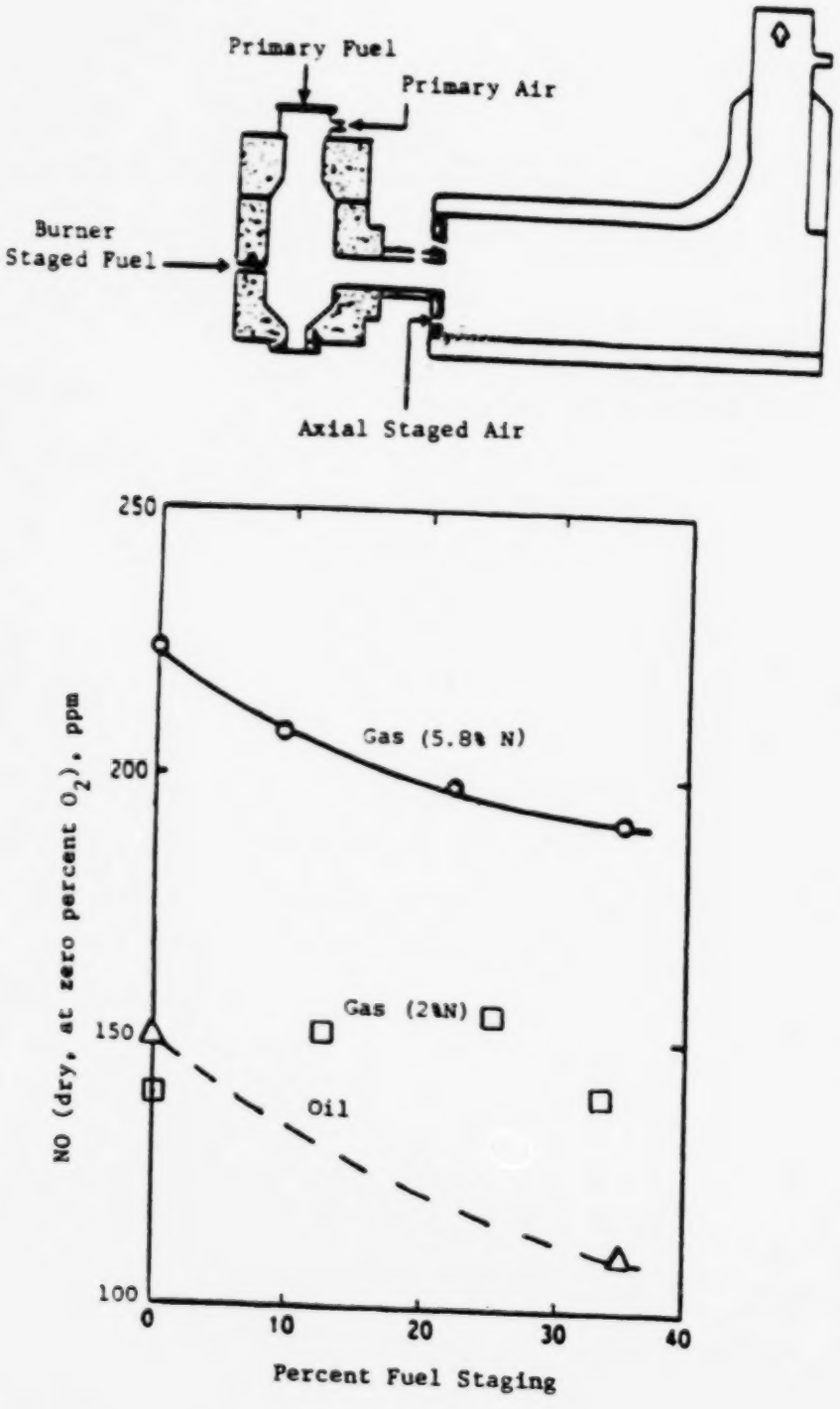


Figure 4-8. Burner fuel staging results. Shown are results from firing 2.0 percent and 5.8 percent nitrogen gas fuel and a 2.0 percent nitrogen oil mixture.

baseline tests where secondary air was injected radially. This difference can be attributed to a delayed combustion gas/secondary air mixing in the case of axially injected secondary air. The results with 2.0 percent N gas/ammonia mixture need more data for explanation.

Thus with this scheme of fuel staging, under the experimental conditions examined, the NO emissions for 5.8 percent N gaseous fuel firing were not lower than the project goal of 0.2 lb (as NO_2)/10^6 Btu (or approximately 175 ppm at 0 percent O_2).

4.5.2 Boiler Fuel Staging

As in the tests just described, total boiler load was held constant while fuel was diverted from the primary fuel injector to two secondary injectors. In this case, the staged fuel (undoped natural gas) was injected into the boiler downstream of the secondary radial air addition. Thus, a four-stage combustion process was established, consisting of a fuel-rich burner zone and three boiler zones characteristic of reburning (i.e., fuel-lean, fuel-rich, fuel-lean). The stoichiometry in the third stage (SR3, the fuel-rich reburning zone in the boiler) is critical in this NOx control process. As already described, all of the staged air and fuel flows were injected from the front face of the boiler at various angles, resulting in the three boiler stoichiometric zones.

Fuel oil/pyridine and natural gas/ammonia results are given in Figure 4-9. Two second-stage stoichiometries (SR_2) were established: 1.1 and 1.0. The NO emissions under no staging conditions for the cases of 5.8 percent N gaseous fuel firing and 2.0 percent N liquid fuel firing were 315 ppm and 190 ppm. With 35 percent fuel staging and 5.8 percent N gaseous fuel firing, the NO emissions decreased to 195 ppm at a SR2 of 1.1 (and a SR3 of 0.72) and to 160 ppm at a SR2 of 1.0 (and a SR3 of 0.65). Again, with 35 percent fuel staging and 2.0 percent N liquid fuel firing, the NO emissions decreased to 120 ppm at a SR2 of 1.1 (and a SR3 of 0.76) and to 110 ppm at a SR2 of 1.0 (and a SR3 of 0.69). Due to less distinct stoichiometric zones than typically established in reburning application, the decrease in NO levels by fuel staging was not quite as great as that obtained when the staged fuel was injected farther downstream of the fuel-lean primary combustion zone;[12,16] however, the configuration

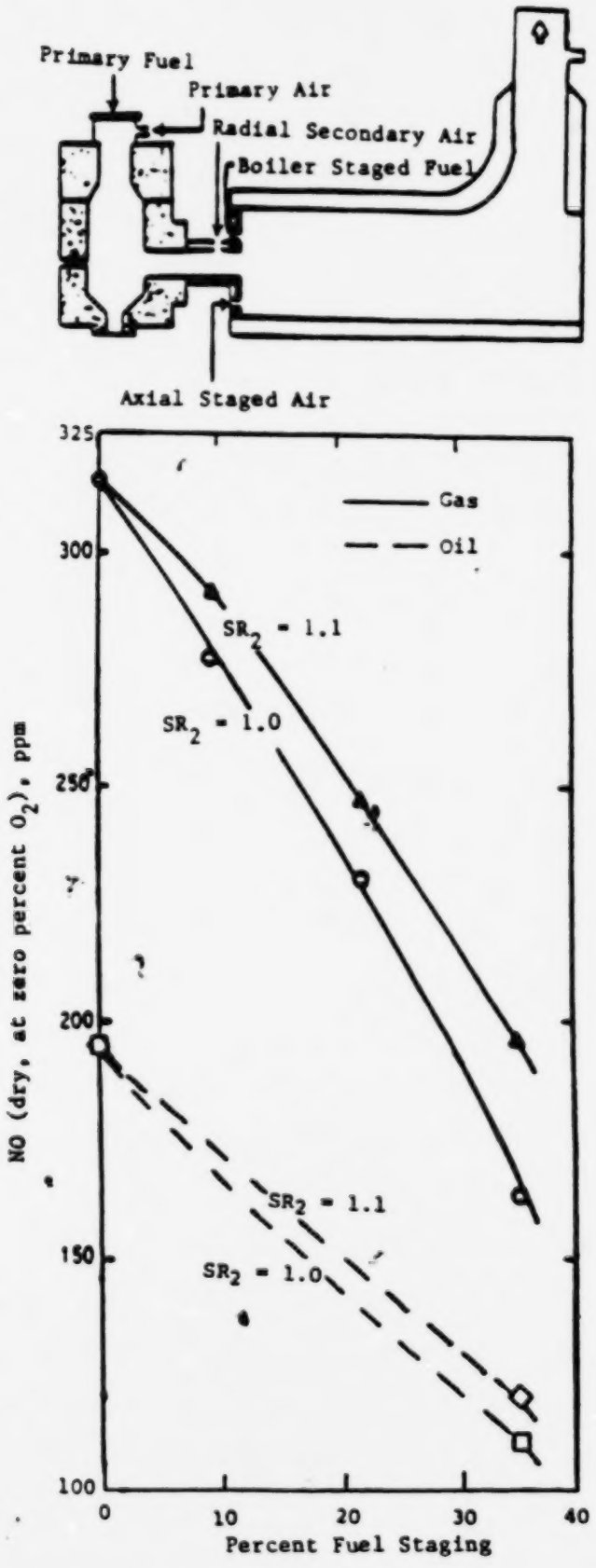


Figure 4-9. Boiler fuel staging results. Shown are results from firing a 5.8 percent nitrogen gas fuel and a 2.0 percent nitrogen oil mixture.

used in these tests requires no boiler penetrations. In addition, complete destruction of the primary fuel/waste stream appears to be ensured by providing all of the required primary combustion air prior to entry into the boiler.

4.6 DISCUSSION AND CONCLUSIONS

Table 4-1 summarizes results from the various combustion modification schemes for the reduction of NO in the oil and gas tests. These results were obtained at optimal first-stage stoichiometries. From the table it can be seen that deep air staging and fuel staging in the boiler (reburning) seem to be most effective in minimizing NO emission, resulting in an overall NO reduction (ppm levels) of about 85 percent. Both configurations—shortened precombustion chamber burner/deep air staging and shortened precombustion chamber burner/boiler fuel staging—met the program goal of attaining NO emissions of approximately 175 ppm from firing gaseous and liquid fuels doped with up to 5 percent nitrogen.

In the case of deep air staging, the decrease in NO emissions is due to a longer fuel rich zone residence time (leading to greater fuel N to N_2 conversion) and adding burnout air at a relatively cooler deep staged air location (thereby generating less thermal NO). However, as mentioned before, this approach does expose boiler walls to a reducing fuel rich zone and may cause sooting or slagging on boiler walls.

In the case of reburning (as applied here), the net decrease in NO emissions seems to be due to a dilution of primary combustion gases by secondary combustion gases. This can be seen in Table 4-2 where NO concentrations obtained after adding appropriate dilution to base NO concentrations are very close to those obtained during corresponding reburning applications. Thus, net chemical destruction of NO during reburning under these experimental conditions does not seem to be evident. This may be because of the existence of rather low primary NO concentrations before applying reburning. However, a beneficial dilution caused by reburning, as applied here, may provide lower NO emissions (on a ppm or $lb/10^6$ Btu basis) along with no loss in heat output. This beneficial dilution aspect of reburning application can be seen by comparing the results of Figures 4-6 and 4-9. Substituting 35 percent of a 5.8 percent N gaseous fuel with a nitrogen-free one would yield a primary N content of 3.77 percent, and from Figure 4-6,

firing this fuel would result in approximately 290 ppm NO. However, for a corresponding case in reburning, NO emission can be as low as 160 ppm.

TABLE 4-1. SUMMARY OF RESULTS

Control Modification	Amount	NO, ppm (percent reduction) Natural Gas/Ammonia	Fuel Oil/Pyridine
Burner Baseline			
• N.A. Burner	—	950	765
• Low NO_x Burner	250 ms	315 (67)	190 (75)
Burner Characterization			
• Excess Air	5%	290 (69)	175 (77)
• Load	65%	260 (73)	140 (82)
• Fuel Nitrogen	1%	200 (79)	150 (80)
Air Staging			
• Axial	100%	220 (77)	150 (80)
• Deep	100%	160 (83)	130 (83)
Fuel Staging			
• Burner	35%	190 (80)	110 (86)
— Boiler	35%		
— SR_2 = 1.1		195 (79)	120 (84)
— SR_2 = 1.0		160 (83)	110 (86)

TABLE 4-2. DILUTION CORRECTIONS

Configuration	Two Stage		Dilution Added To Two Stage	Reburn	Air Staging	
Reference Figure	4-5			4-9	4-7	
Waste Load	100%	65%	65%	65%	100%	100%
Fuel				(SR_2 = 1.0)	Axial	Deep
No. 2 Fuel Oil/Pyridine (2% N)	190	135	88*	110	150	130
Natural Gas/Ammonia (2% N)	185	130	--	--	--	--
Natural Gas/Ammonia (5.8% N)	315	260	169*	160	220	160

* Calculations showing the addition of dilution:
Natural gas/ammonia (5.8 percent N): 0.65 x 260 ppm = 169 ppm
No. 2 fuel oil/pyridine (2.0 percent N): 0.65 x 135 ppm = 88 ppm

SECTION 5

QUALITY CONTROL EVALUATION REPORT

5.1 INTRODUCTION

The quality assurance objectives of this project were to assure that 1) the combustion conditions in the furnace were representative of the intended experimental design, and that 2) the collected data were accurate and useful. The QA/QC procedures documented in the Quality Assurance Project Plan required that all continuous monitors and other measurement instruments, where possible, be carefully calibrated using manufacturer's procedures or other published methods. Zero and span checks were performed each test day on the continuous monitors. Annual calibrations of air flow and gas flow devices were also performed. These data are documented.

5.2 DISCUSSION OF DATA QUALITY

A summary of the precision, accuracy, and completeness achieved in the relevant measurements is listed in Table 5-1, along with the original goals for each type of measurement. In all cases, the completeness, accuracy, and precision of measurements met or exceeded the Quality Assurance objectives listed in the Quality Assurance Project Plan (QAPP) developed for the project.

Primary, secondary, and tertiary air flows on the Low NO_X facility were measured by venturi arrangements. Precision of these venturis was checked annually during the test program. The precision check procedure for these venturis consisted of the following steps:

1. Close the damper on the stack of the low NO_X facility operating with this causes the in-furnace pressures to be positive and eliminates in-leakage.
2. Vary each of the airs (primary, secondary, and tertiary) individually and read excess air levels against a previously calibrated oxygen monitor. Now knowing that 9.69 mol of air are required per mole of natural gas (refer to house natural gas analysis5), curves can be plotted relating pressure drop across the respective venturis to respective air flows in scfm.

TABLE 5-1. DATA QUALITY SUMMARY

Parameter (Method)	Completeness (%)		Precision (%)		Accuracy (%)	
	Planned	Actual	Planned	Actual	Planned	Actual
NO (Chemiluminescence)	a	>90	a	4.407	2.5	1.460
CO (NDIR)	a	>90	a	1.907	5	0.547
CO_2 (NDIR)	a	>90	a	2.482	5	-2.722
O_2 (Paramagnetic)	a	>90	a	2.218	2.5	-1.504
Primary Air Flows (b)	a	>90	a	0.084 (% RSD)	a	c
Secondary Axial Air Flows (b)	a	>90	a	0.047 (% RSD)	a	c
Secondary Radial Air Flows (b)	a	>90	a	0.049 (% RSD)	a	c
Tertiary Air Flows (b)	a	>90	a	0.084 (% RSD)	a	c
Primary Gas Flows (b)	a	>90	a	c	5	c
Secondary Gas Flows (b)	a	>90	a	0.10 (% RSD)	5	c

a. Objectives were not defined in the QAPP
b. See Section 5.1 for explanation
c. Not done during the program

The primary natural gas flow used in the above calibration was measured by an orifice which had been calibrated against a dry gas meter. Prior to air calibration, the natural gas orifice was inspected and recalibrated if necessary.

Secondary gas flows on the low NO_x facility were measured by a rotameter. These flows were also calibrated using the scheme outlined above for the various air flows.

An overall facility precision check was performed each test day by repeating an arbitrarily selected "baseline" data point at the end of a test sequence. If the NO and O_2 monitor readings were within 10 percent precision for the two baseline measurements, then overall facility operation was considered to be consistent.

NO_2, NO_3, N_2O, NH_3, HCN, and combustion gas velocity measurements were not made during this program. Hence, Quality Assurance objectives for these parameters were not completed.

Primary natural gas flow venturi, thermocouples measuring process temperatures, Bourdon gauges measuring process pressures, and suction pyrometer measuring combustion gas temperatures were inspected periodically and found to be in good working order. Hence, accuracy of these elements was not checked.

In summary, the collected data are sufficient for the original intentions of the project.

SECTION 6

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